ARCTIC SPRING TRANSITION IN A WARMING CLIMATE:

ANALYSIS BY USING A REANALYSIS DATASET

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A

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Abstract

An increased warming trend over the Arctic in recent years has been documented using observations, and is expected to continue by climate model projections. This increase may shift the springtime transition time, causing an earlier onset of summer and resulting in a longer sea-ice melt and vegetation growing period over the Arctic. In this study, we investigated variability of and changes in the spring transition in a warming climate and examined attributions of various dynamic and thermodynamic processes. The results demonstrate a dramatic increase in springtime surface air temperature (SAT) over the Arctic since 1979. Physical analysis reveals an increase in poleward moisture and latent heat transport accompanied by an enhancement of cloud cover, which result in positive downward longwave radiation. A persistent increase in poleward warm air advection is also found; leading to sensible heat flux from the warmer atmosphere to the surface furthering the surface warming. Retreat of sea ice cover reduces surface albedo, making an additional contribution to the surface warming. In addition to the overall evaluation of these physical processes, composite analysis suggests that relative contributions from these processes to the increased springtime SAT vary across different geographic sub-regions.

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Chapter 1 Introduction

1.1 Overview and Motivation

According to the US Arctic Research Commission (1999) "change in the Arctic may play a substantial role in climate change throughout the globe" and moreover "global change, particularly climate change may have its most pronounced effects in the Arctic" (NOAA 2014). The Arctic is still a less explored area but critically important to global climate system. During recent decades the Arctic has warmed more compared to global average and the Arctic sea ice coverage has decreased significantly. An Information Statement of the American Meteorological Society on Climate change (2012) indicates "…the effects of this warming are especially evident in the planet's polar regions. Arctic sea ice extent and volume have been decreasing for the past several decades" (AMS 2014). The continued future trend in warming and retreat of sea ice over the Arctic is supported in IPCC 5th assessment report which says "the Arctic will warm more rapidly than the global mean" and "it is very likely that the Arctic sea ice cover will continue to shrink and thin".

The climate change signal in Arctic during recent years includes a rapid increase in surface air temperatures (SAT) over the Arctic (Chapman and Walsh 1993, Rigor et al. 2000); retreat in glaciers especially over Alaska and west Canada region (Arendt et al. 2006); enhanced pole-ward moisture transport and amplified wetting trend (Zhang et al. 2013) and increased storminess over high latitudes (McCabe et al. 2001, Zhang et al. 2004). Also accelerated reduction in Arctic sea ice (Comiso et al. 2008) and significant reduction in summer sea ice extent (Holland et al. 2006) are leading to a possibility of having seasonally ice free Arctic Ocean (Zhang and Walsh 2006, Wang and Overland 2009) in the future. The visual projection of the following figure shows retreat in Arctic sea ice extent in September, which reinforces the possibility of seasonally ice free Arctic in future (Figure 1.1)

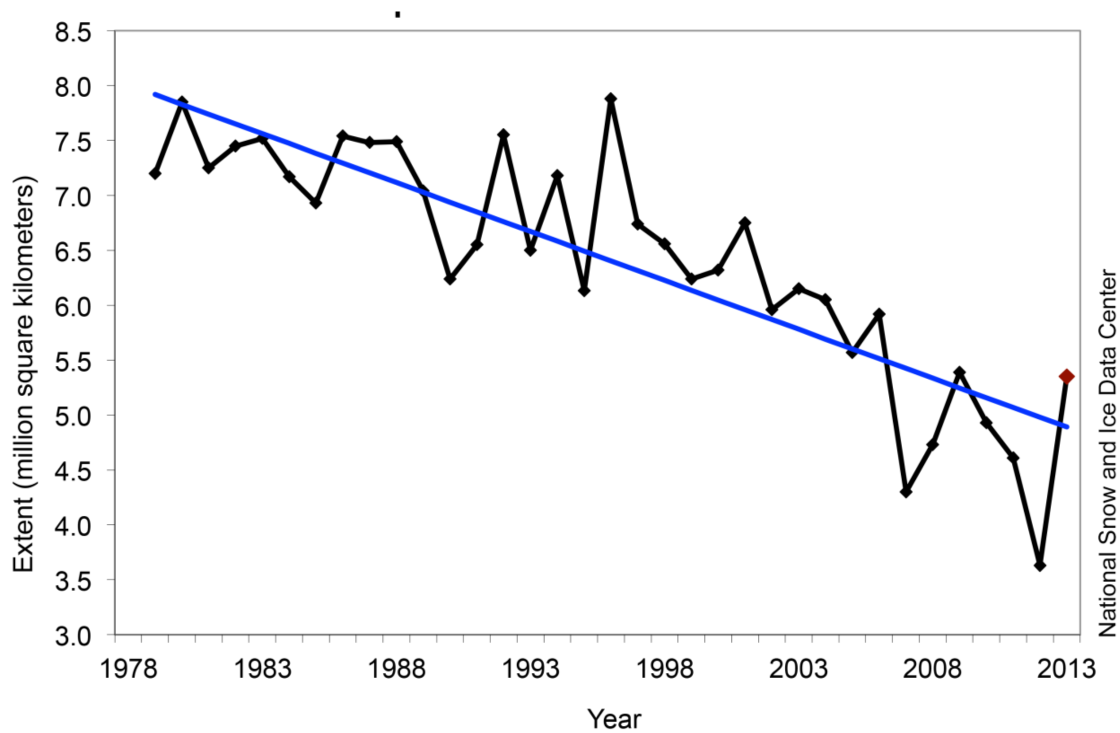

Figure 1.1: Dramatic decreasing trend in average monthly Arctic sea ice extent during September for 1979 to 2013 shows a decline of 13.7% per decade relative to 1981-2010 average.(available online: http://nsidc.org/arcticseaicenews/2013/10/a-better-year-for-the-cryosphere/). Retreating sea ice is reinforcing the possibility of having seasonally ice free Arctic Ocean.

1.2 Impact of Arctic Climate Change

The poorly explored Arctic is experiencing the most pronounced effect of climate change with enhanced and rapid warming rate compared to overall global warming. The warming trend in the Arctic can trigger possible changes in ecosystem, increase in vegetation (Bhatt et al. 2010) and impacts on the climate sensitive livelihood of indigenous habitat with vulnerabilities for community life and harvesting activities (Ford et al. 2006). Retreat in sea ice could be economically important for possibility of easier mining and shipping activities (Stewart et al. 2007) and the abrupt decline with the warming trend (Comiso 2006) could be a threat for habitat like polar bears.

Arctic climate change can have a significant global scale signature such as increased sea level rise (Arendt et al. 2002) and more persistent extreme weather events in mid-latitudes (Ford et al. 2006; Francis and Vavrus 2012) and anamolous winter snowfall in parts of the northen hemisphere (Liu et al. 2012). Associated with Arctic warming the retreat in sea ice can also impact the large scale circulation over the Euro-Atlantic region (Balmaseda et al. 2010) and can, furthermore, alter northern hemispheric atmospheric circulation during fall (Overland and Wang 2010).

An important consequence of Arctic warming would be possible changes in seasonal climatology. Changes in seasonal transition during spring in warm climate conditions would be important as it can favors a longer summer associated with above mentioned difficulties. A proper understanding of the Arctic climate system, changes in its seasonal climatology and the causes behind the warming trend is important for the scientific community as well as the policy makers to identify this important climate signal emerging in recent years.

1.3 Arctic Warming and Contributing Factors

Since the advent of satellite remote sensing era in late 1970s, continuous monitoring shows that arctic sea ice and snow cover have been reduced in last 30 years from the enhanced warming over the Arctic. The shrinking sea ice cover is warming up the overlying atmosphere strongly through complex mechanisms and can trigger positive feedback within the system to cause further warming. Due to strong surface albedo, sea ice reflects most of incoming solar energy back to the space. But with retreating sea ice, considerable open sea surface is exposed that can absorb more incoming solar energy due to low surface albedo. These result in warming over the Arctic which leads to more sea ice melting and can cause further warming, known as Arctic Amplification.

The Arctic Amplification is resulting in greater SAT change and variability over the high latitudes than global average and expecting to strengthen in future. While reduced sea ice and ice-albedo feedback are termed as the key factor for Arctic Amplification, different factors such as changes in atmospheric and oceanic circulation, water vapor, cloud cover and aerosol concentration also have important contribution in the warming trend (Serreze and Barry 2011).

Figure 1.2 shows in the last decade the Arctic experienced significant positive temperature anomaly compared to long term climatology that demonstrates evident warming trend over the whole Arctic.

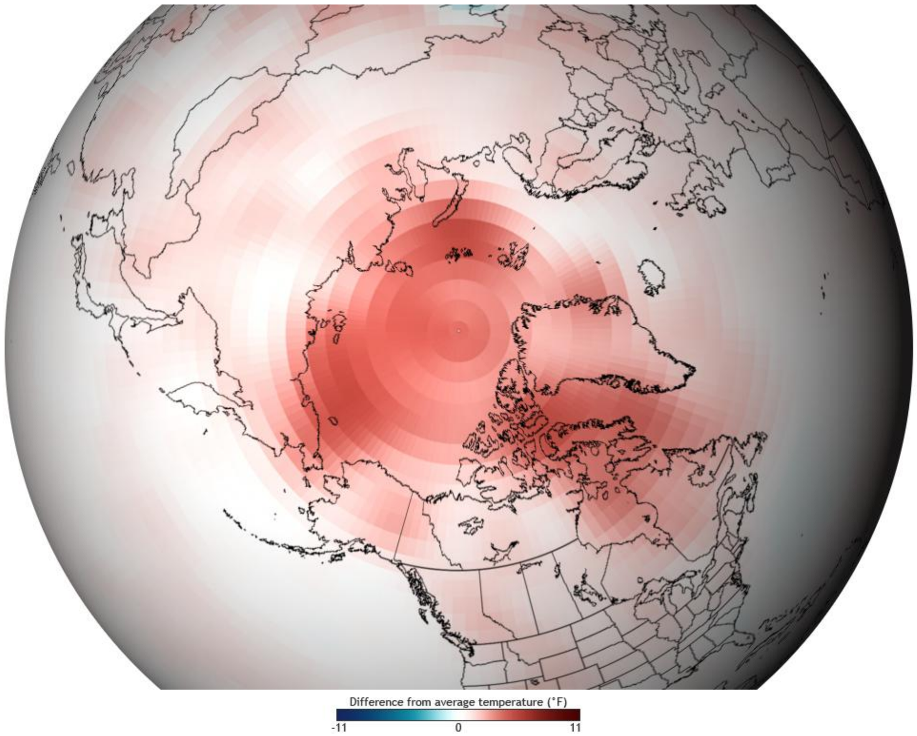

Figure 1.2: The positive anomaly in decadal average temperature for 2001-2011 compared to 30 year climatology (1971-2000) demonstrates the warming trend over the whole Arctic. (Source: http://www.climate.gov/news-features/featured-images/arctic-temperature-patterns-2012-and-2001-2011) Over the span of the last decade Arctic amplification is evident as no part of the Arctic was cooler than the long-term average.

The evident Arctic warming trend can impact the global climate and influence the seasonal climatology over Arctic. A number of different physical parameters can influence the Arctic climate system. A detailed understanding of contributing dynamic mechanisms and thermodynamic processes that together determines the Arctic surface energy budget is needed for future climate projection. Investigating the attribution of the different physical parameters like large scale atmospheric energy and moisture inflow from the mid-latitudes into the Arctic, impact of sea ice retreat, increasing cloudiness and interaction with global circulation with regional thermodynamic feedback mechanisms, can reveal the underlying physics of the Arctic warming. A better understanding and future projection of the Arctic warming would be necessary for the scientific community and policy makers for appropriate mitigation and adaption techniques.

1.3.1 Global Atmospheric Circulation

This differential solar heating gives rise to atmospheric and oceanic circulation to attain the radiative equilibrium of the earth as a whole by poleward transport of energy from the tropics (Figure 1.3).

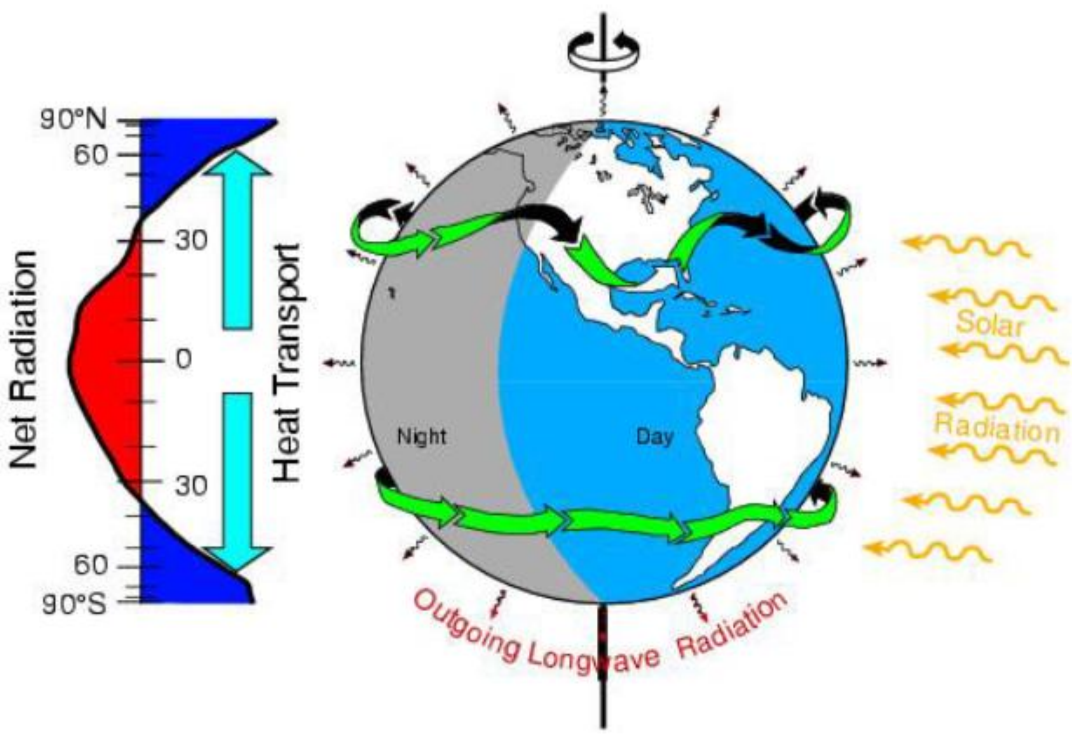

Figure 1.3: Differential solar heating results in meridional heat transport to attain the global radiative equilibrium (source: http://www.cgd.ucar.edu/cas/Topics/cchange.html).

The net global radiation budget introduces a surplus of heat energy over the tropics and a deficit over the pole. If we consider the earth as a heat engine, the Arctic acts as a large heat sink of the system. More heat escapes into the space than received over the Arctic which is balanced by transport of large amounts of energy from lower latitudes. Thus the Arctic warming and large scale atmospheric circulation can impact each other.

1.3.1.1 Convergence of Energy and Moisture into Arctic

The Arctic is critically important for maintaining the energy balance of the earth and the global circulation. Variation in atmospheric energy transport processes into the Arctic can have a significant effect on the Arctic temperature field (Graversen et al. 2011) and moisture transport can influence the snow, sea ice and ice sheet over Arctic (Oshima and Yamazaki 2004). Unusual warm and humid condition can prevail due to increased atmospheric energy transport, similar to the observed pattern during the 2007 and 2005 extreme ice loss event (Graversen et al. 2011). Enhanced energy and moisture convergence during the springtime into the Arctic can increase the cloudiness and atmospheric opacity and thus the greenhouse effect which could be responsible for increased surface energy flux and enhanced ice melt (Kapsch et al. 2013). Recently a faster shrinkage in sea ice in summer than winter had been observed (Zhang and Walsh 2006). Sensitivity of arctic SAT to increased atmospheric northward energy transport (ANET) (Graversen 2006) is reinforced by impact of local factors like summer sea ice retreat and early melting of snow on Amplification of Arctic Surface Air Temperature (Serreze and Barry 2011). Also distinct seasonality is observed between the changes in summer sea ice area (SIA) with surface air temperature (SAT) with a strong correlation during springtime (Figure 1.4) that indicates drastic change during melting season compared to freezing season (Zhang 2010).

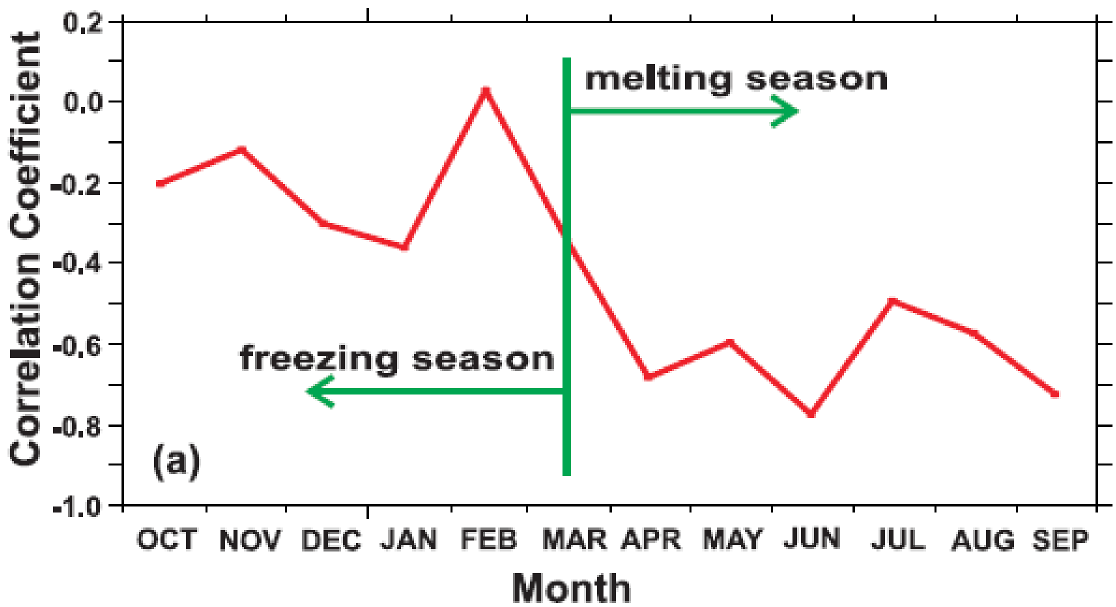

Figure 1.4: The lag- correlation coefficients of SIA and Arctic regionally averaged SAT shows the seasonality of summer sea ice response to SAT (Zhang 2010).

Since changes in energy and moisture transport into the Arctic plays a key role to regulate SAT, it can also has significant impact over the observed changes in seasonality in Arctic due to enhanced surface warming. This study motivates to investigate seasonality between surface air temperature and contributing physical factors.

1.3.2. Surface Energy Budget over the Arctic

The surface energy budget of Arctic is influenced by both advected energy from the lower latitude, regional radiative and turbulent heat fluxes.

Radiatively, the surface energy budget is basically a balance between incoming shortwave radiation with outgoing reflected shortwave radiation and outgoing terrestrial long wave radiation. Reflectivity and absorbitivity of the Earth's surface and atmosphere are important factors for the surface radiation budget of the earth.

$$R_{net} = SW\ (1\text{-}A) + LW\ (in)\text{-}LW\ (out) \qquad (1.1)$$

Where, R_{net} is net radiative energy flux, SW is shortwave radiation flux, LW is longwave radiation flux and A is surface albedo.

The energy balance at the earth surface is also influenced by continuous exchange of energy between ground and the overlying atmosphere as available energy is transformed into sensible and latent heat. From the conservation of energy at the earth's surface the balance between net radiation (Rnet) impinging the surface with non-radiative sensible heat flux, latent heat flux and ground heat flux would be,

$$R_{net} = \text{Sensible Heat (SH)} + \text{Latent Heat (LH)} + \text{Ground heat (GH)} \qquad (1.2)$$

For large diurnal variation ground heat flux (GH) can be ignored over a time period.

So, the important components of net surface energy budget (Enet) would be net surface shortwave (SWnet) and longwave (LWnet) radiation fluxes and sensible (SH) and latent (LH) heat turbulent fluxes at surface (Graversen et al. 2011).

$$Enet = SWnet + LWnet + SH + LH \qquad (1.3)$$

The below schematic representation (Figure 1.5) shows the component of Arctic energy budget using energy and moisture advection from mid-latitudes and different radiative energy fluxes over the Arctic as well..

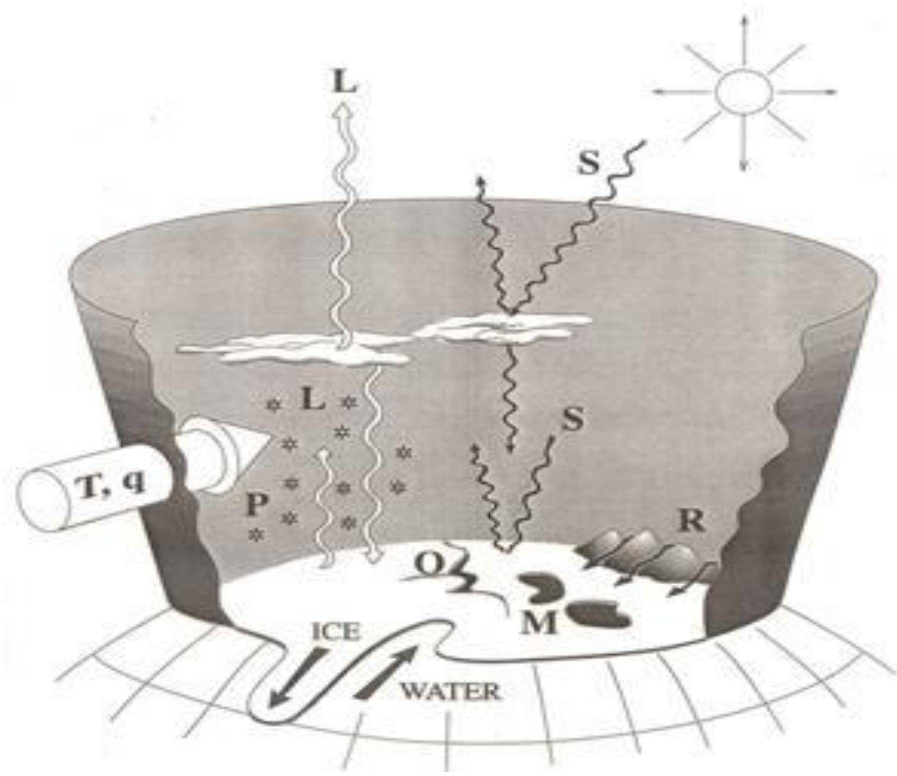

Figure 1.5: Schematic representation of Arctic Energy Budget where R = Runoff (freshwater), L = Longwave radiation, S = Shortwave radiation, O = Ocean heat, M = Melt (snow and ice), P = Precipitation, T = Temperature (heat transfer), and q = moisture. (Credit: N Untersteiner 1993; source**:** http://nsidc.org/cryosphere/arctic-meteorology/effects_of_climate_weather.html).

1.3.2.1 Effect of Cloud and Snow Cover

Cloud and snow cover can play an important role for controlling the SW and LW radiation budget for the Arctic surface. Clouds impact the surface energy budget of the earth. They cool by reflecting incoming shortwave solar radiation and they warm by absorbing and reemitting long wave terrestrial radiation. Net surface radiative forcing is the sum of net LW and net SW radiation received by the surface. Shortwave cloud radiative forcing acts to cool the climate, while longwave cloud radiative forcing acts to warm the surface. During springtime, in the snow melt period, positive cloud radiative forcing can enhance lower tropospheric warming and thus accelerate melting of snow (Zhang et al. 1997). Seasonality of cloudiness over Arctic has reported more cloud cover during spring and summer (Wang and Key 2003) which can enhance sea ice melt from increased downwelling longwave radiation (Zhang et al. 1997). Surface albedo plays an important role for the surface energy balance; the seasonal snow cover of the Arctic can affect the interaction with clouds and thus the surface energy balance. The energy needed for melting of snow in Arctic is mainly provided by the radiative fluxes and thus variation in cloudiness can cause interannual variability of snow melting time (Serreze et al. 1993). Due to the influence of surface albedo, the onset of snow melt is important for the surface energy budget in the Arctic. Increases in spring cloud cover can change the surface albedo and alter the surface radiation budget significantly to initiate an earlier onset of summer in the Arctic.

1.4 Objective of the Study

Recent increases in surface air temperature associated with Arctic amplification can change the seasonality over Arctic. The current study addresses scientific problems on changes in seasonal climatology over the Arctic due to the observed warming trend. The studies and theories presented in previous sections reveal that the Arctic surface energy budget and therefore the surface air temperature are influenced by different dynamic and thermodynamic factors. To understand the impact of changing climate patterns on seasonal climatology, we need to investigate the different contributing physical factors that influence the surface air temperature field.

The energy and moisture budget in the Arctic plays a crucial role in warming and can have a major influence on the seasonality of the Arctic. A better understanding of the partitioning of the energy and moisture budget would help to understand which term is more important for regulating Arctic SAT. The changing scenario of different radiative and turbulent energy flux components at the surface would also be useful evidence for analyzing the impact of thermodynamic factors on the seasonal variation of arctic SAT. Our aim is to study how the Arctic surface energy budget is influenced by different complex dynamic and physical mechanisms and how changes in those contributing factors can regulate the surface warming pattern. Anomalous warming patterns will lead to changes in the seasonal climatology, with shorter winter and longer summer periods. Any significant change in the seasonal climatology of spring time would be crucial for determining the existence of a tipping point for increasing the summer period.

The main goal of this work is to investigate the impact of warming in the Arctic in the context of seasonality. We specifically chose the seasonal transition during springtime for our study as spring is an important seasonal transition period from the long, dark and cold Arctic winter to the Arctic summer and any changes during spring transition would be critical for melting and framing the onset of summer. We examine how the seasonal spring transition over the Arctic is changing over time leading to a longer summer, early melting and lengthening of growing season and potential chances to have seasonally ice free Arctic Ocean in near future. The thesis presents a diagnostic analysis of dynamic factors such as energy and moisture transport as well as thermodynamic processes like influence of radiative and non radiative energy fluxes to investigate the seasonality of Arctic SAT for interpreting seasonal changes during the spring.

The ultimate goal of the study is to improve our understanding of physical processes that shape climatology and variability of the Arctic spring transition.

The thesis is organized as follows. Chapter 2 presents the contributing physical parameters that regulate the changing seasonal climatology pattern. Chapter 3 contains an analysis of possible causes behind the year-to-year variability in the warming trend over the Arctic. The conclusions and discussion from the study are presented in Chapter 4.

Chapter 2 Arctic Springtime Transition

2.1 Introduction

This chapter presents the study of seasonal climatology of Arctic to understand observed changes in seasonality. We use diagnostic analysis and interpretation of atmospheric general circulation and physical processes governing moisture and energy budget, to study the impact of changing climate to identify important climate signals in seasonality over Arctic. As climate change is more pronounced over the high latitudes than in the global average, the Arctic is experiencing changes like rapid warming, enhanced sea ice and glacier melt, increased cloudiness and changes in precipitation patterns. A concern is raised on how these rapid changes could be important for different thermodynamical and dynamical processes controlling the climate system. The focus of the study presented here is pertains to the dynamics of the springtime transition over the Arctic, how the spring transition over the Arctic is changing over time and the possible causes of outstanding changes in the Arctic spring transition.

We are trying to improve our understanding of thermodynamic mechanisms of the Arctic energy budget and their linkage to dynamic processes to see how this is reflected in seasonal changes in the Arctic during springtime as a broader impact of this work.

2.2 Datasets and Methodology

We use atmospheric reanalysis data for climate variables that are needed in the statistical and numerical calculation for this study. According to the NCAR Climate Data Guide reanalysis data is basically a systematically produced dataset for climate research and it incorporates all available data for a particular period using stable, unchanging data assimilation system and models.

2.2.1. Reanalysis Dataset

For the study we use data from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis-2 which covers the post -1979 periods. This reanalysis data, provided by NOAA Earth System Research Laboratory, is an improved version of NCEP reanalysis -1 reanalysis with improved physical parameterizations and an updated data assimilation system (Kanamitsu et al. 2002). The NCEP NCAR reanalysis project uses a variety of available data integrating observations from satellites, buoys, radiosondes, aircrafts and other sources. A stable analysis/forecast system for global data assimilation is used to generate consistent, long term climate data (Kalnay et al. 1996, Kanamitsu et al. 2002, Amenu and Kumar 2005). This global dataset can explicitly describe climate variability (Zveryaev and Chu 2003, Amenu and Kumar 2005). The NCEP reanalysis data-2 is provided at varying spatial resolution and different temporal resolutions including 6-hourly, daily and monthly from 1979 to present.

We obtained the dataset from NOAA–Earth System Research Laboratory (ESRL) website for our study. We used air temperatures, wind field, relative humidity, cloud cover, short wave and long wave radiation fluxes, turbulent heat fluxes and sea ice concentration at a 6 hourly temporal resolutions for our long term analysis over the Arctic. Our research area focuses on a region from 60°N to 90° N for 1979-2012 periods.

However it should be noted that, NCEP-NCAR reanalysis -2 is still a first generation reanalysis data with low spatial and moisture variability over the ocean.

2.2.2. Features for Reanalysis Datasets:

The key features of the NCEP-NCAR reanalysis-2 data are (NOAA, 2013) as follows:

Spatial Coverage: The pressure Level data is available at a 2.5°-latitude x 2.5°-longitude global grid (144x73) with a spatial coverage of 90°N - 90°S, 0°E - 357.5°E. The Gaussian Grid data is available at the T62 resolution of the Gaussian grid (192x94) with a spatial coverage of 88.542°N-88.542°S, 0°E-358.125°E.

Temporal Coverage: The data is available at 4 Times daily (6 hourly), daily and monthly values.

Levels: The Pressure Level data is available in 17 pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 hPa). The Gaussian Grid data is available at different levels such as Surface or near the surface, nominal top of atmosphere (NTAT), entire atmosphere as a column and cloud pressure levels.

2.2.3. Specific Parameters used:

For the study we used different parameters from pressure level data at 6-hourly resolution in the global grid (144x73) for parameters including air temperature, geopotential height, relative humidity, zonal and meridional wind. We used Gaussian grid data in global T62 Gaussian grid (192x94) in 6-hourly temporal resolution at surface level for parameters including sea ice concentration, downward solar radiation flux, upward solar radiation flux, downward longwave radiation flux, upward longwave radiation flux, total cloud cover, latent heat flux and sensible heat flux.

2.2.4. Employed Methods

The study evaluates the surface air temperature (SAT) trend for the Arctic at north of 60°N for the spring transition over the period during 1979-2012. We also investigate the mid-latitude region from 40°N to 60°N to study linkages of large scale atmospheric dynamics on physical processes over the Arctic (Figure 2.1).

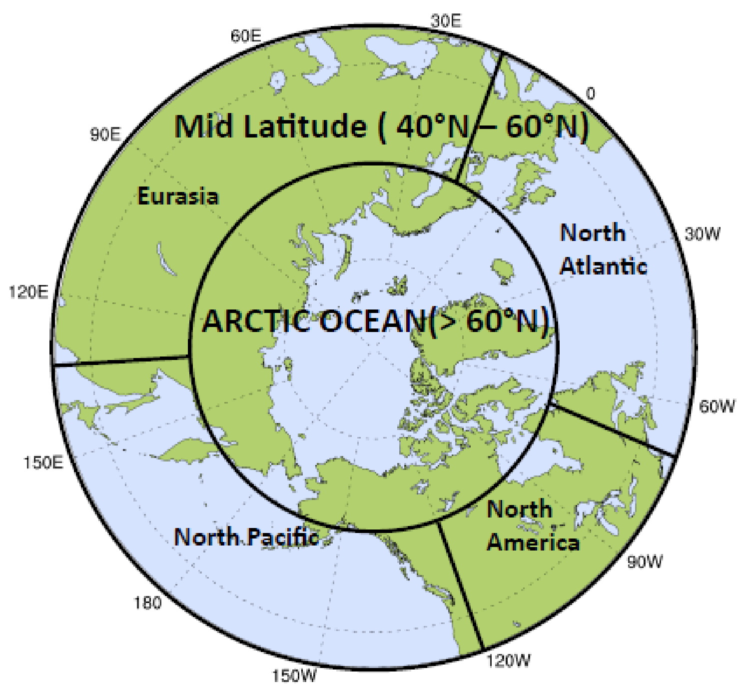

Figure 2.1: The area of interest in our study is the whole Arctic (60°N -90°N). To study the linkage of large scale dynamics with Arctic surface energy budget we investigate the mid-latitude region (40°N to 60° N) which is further divided into North Pacific, North America, North Atlantic and Eurasia.

In our study to represent regional importance, the mid-latitude region is divided into four sectors: the North Atlantic (70°W–20°E), the North Pacific (140°E–120°W), Eurasia (20°–140°E), and North America (120°–70°W) .

To examine the factors influencing the SAT trend we employed analysis of different dynamic and thermodynamic parameters for the same time period and region. We examine the SAT trend and different thermodynamic processes that influence the surface energy budget over the Arctic as well as contribution s of different dynamic factors over the mid-latitude region to regulate the surface energy budget and SAT field over the Arctic.

2.2.2.1 Transport Calculation

We use physical variables given in pressure coordinate to calculate moisture and energy convergence into the Arctic to investigate the influence of dynamic factors on the SAT field. The transport into the Arctic is estimated with 6-hourly resolution by vertically integrating flux through the atmospheric column. Net moisture flux <qv> transported into the arctic is expressed as:

$$\langle qv \rangle = 1/g\int_{300hPa}^{psurface} \boldsymbol{qv}\, dp \qquad (2.1)$$

where q is specific humidity, **v** is horizontal wind vector, g gravitational acceleration and p pressure. The upper limit of the integration is set to 300 hPa because moisture above 300 hPa is negligible.

Thermal energy is carried from the tropics into the Arctic as latent and sensible heat energy. The dry static energy (DSE) or sensible heat energy flux is defined as sum of enthalpy (CpT) and potential energy (gz):

$$DSE = (CpT) + (gz) \qquad (2.2)$$

where , g is gravitational acceleration Cp is specific heat capacity of moist air at constant pressure, T is temperature and z is geopotential height. DSE combined with latent heat energy (Lq) gives moist static energy or total atmospheric energy fluxes. Moist static energy (MSE) is defined as sum of enthalpy (CpT), potential energy (gz) and latent heat energy (Lq).

$$MSE = (CpT) + (gz) + (Lq) \qquad (2.3)$$

where g is gravitational acceleration, Cp is specific heat of moist air at constant pressure, T is temperature, z is geopotential height, L is specific heat of condensation and q specific humidity.

Vertically integrated atmospheric energy fluxes for each energy component are given by:

$$\langle CpT \rangle = 1/g\int_{\boldsymbol{ptop}}^{\boldsymbol{psurface}}(\boldsymbol{CpT})\boldsymbol{v}\ dp \qquad (2.4)$$

where g is gravitational acceleration, **v**(u,v) is horizontal wind vector, Cp is specific heat of moist air at constant pressure, T is temperature;

$$\langle gz \rangle = 1/g\int_{\boldsymbol{ptop}}^{\boldsymbol{psurface}}(\boldsymbol{gz})\boldsymbol{v}\ dp \qquad (2.5)$$

where g is gravitational acceleration, **v**(u,v) is horizontal wind vector, Cp is specific heat of moist air at constant pressure, z is geopotential height; and

$$\langle Lq\rangle = 1/g\int_{\boldsymbol{300hpa}}^{\boldsymbol{psurface}}(\boldsymbol{Lq})\boldsymbol{v}\ \mathrm{dp} \qquad (2.6)$$

where g is gravitational acceleration, **v**(u,v) is horizontal wind vector, Cp is specific heat of moist air at constant pressure, L is specific heat of condensation and q specific humidity. All the climate parameters used here are at a 2.5°×2.5° spatial resolution. The upper limit of the integration in Equation 2.6 is set to 300 hPa because moisture above 300 hPa is negligible.

To calculate convergence across 60 °N latitude into the Arctic we did line integration of each vertically integrated flux (<F>) across the latitudinal boundary of the region using:

$$\langle F\rangle = \int[1/g\int\langle F\rangle \mathrm{dp}]\mathrm{dl} \qquad (2.7)$$

where F is each vertically integrated flux, g is gravitational acceleration, l is length across the 60°N latitudinal boundary. The transport of flux across the boundary of the region is equal to convergence of the given flux into that particular area.

2.3 Surface Air Temperature Analysis

The surface air temperature (SAT) of the Arctic has increased in recent years reaching the highest temperatures in last decade compared to climatology (Walsh et al. 2011). With this “Arctic Amplification” the region is getting warmer with considerable changes in seasonality for increasing SAT trend. During springtime Arctic SAT can reaches a warmer temperatures sooner leading to an earlier spring transition resulting in a longer summer, enhanced melting and growing periods over the Arctic.

In this study we analyzed the changes in springtime (February to May) SAT over the Arctic to understand the seasonal transition trend in terms of changes in surface warming during 1979-2012 period. The time series of area averaged 6-hourly SAT over Arctic shows a prominent increasing trend over time supporting the enhanced warming trend (Figure 2.2) during springtime.

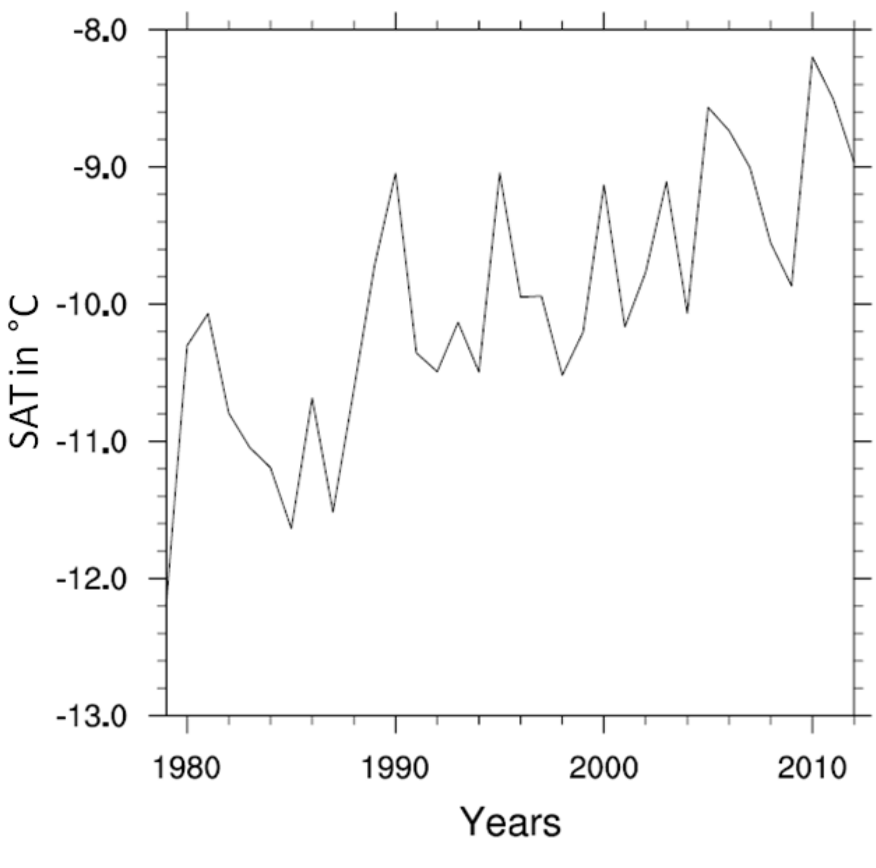

Figure 2.2 Time series for SAT in °C during spring over the Arctic for 1979-2012 period shows temperature has increased over time.

The springtime SAT is increasing significantly with interannual variations superimposed on the trend. Also the springtime SAT anomaly over Arctic compared to long term climatology from 1979-2012 over Arctic supports the increasing temperature trend. It shows a sustained positive anomaly for spring during the last decade of our study and a persistent positive anomaly for the last two decade of the study for March-mid-April period (Figure 2.3).

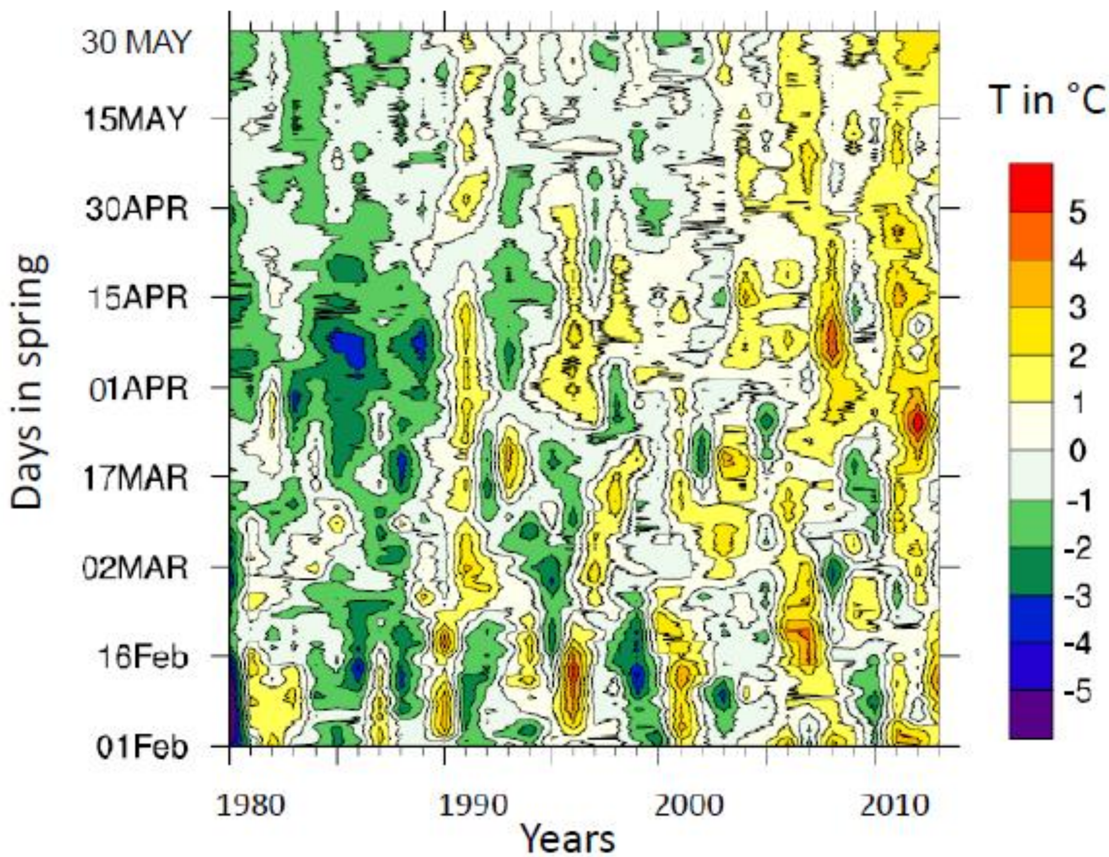

Figure 2.3: Daily SAT anomaly compared to 1979-2012 climatology during springtime over the Arctic shows positive anomaly in spring SAT during last decade of the study.

The isotherms during the spring transition period have a distinct slope in recent years indicating a shift in occurrence time of higher temperature values over the Arctic. The trend of a specific isotherm, say -10 °C, has shifted since the 1980s from around mid-April to mid-March around 2010s, i.e. a shift of nearly one month (Figure 2.4).

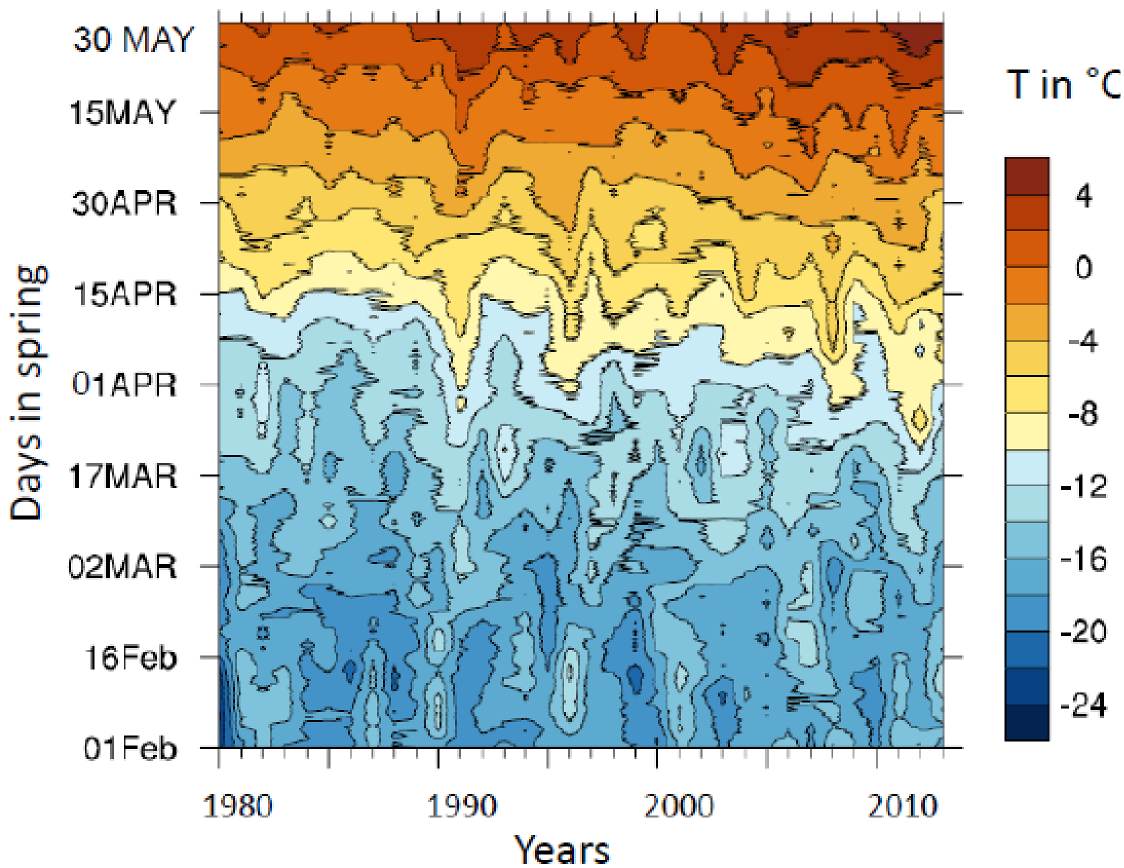

Figure 2.4: Contour plot for isotherms (SAT in °C) during spring for 1979-2012 periods shows shift in the timing of the temperature transition. This is consistent with early warming and sooner onset of spring over the Arctic.

This shift is prominent for the mid-March to mid-April period. This shift in the timing of the temperature transition time is consistent with an earlier onset of spring.

2.3.1 Summary for SAT trend

The spring transition period over the Arctic is changing with time. This evaluation of SAT trend validates that spring transition over the Arctic is associated with an increasing SAT trend.

The changes in SAT are significant during the mid-March to mid-April period as warming has occurred earlier. The maximum transition period of the isotherms has shifted towards mid-March from mid-April period by introducing a rapid transition in SAT.

A shift in transition time during mid-March to mid-April period favors an earlier onset of warmer temperatures. It can favor a reduction of the length of the winter period and enhance the summer period over the Arctic. The analysis suggests an earlier onset of higher surface air temperature can alter the spring transition pattern in recent years.

Analysis of important physical processes for shaping the climatology of the surface energy budget over the Arctic are needed to understand observed variability in SAT and corresponding changes in spring transition.

2.4 Arctic Surface Energy Budget Analysis

We analyzed the moisture and energy budget to investigate dynamic and thermodynamics processes contributing to the climatology and variability of Arctic spring transition. Our study examines the physical processes which influence the surface energy budget and thus the surface air temperature (SAT) to demonstrate the nature and trend of the spring transition in a warming Arctic climate. The atmospheric global circulation can affect the surface energy budget and SAT trend dynamically by controlling heat transport from the mid-latitudes into the Arctic. The poleward transport of warm and humid air influences different thermodynamical process that can regulate the energy budget over the Arctic. The increasing warming trend and the superimposed year-to-year variability of SAT are attributed to both dynamic and thermodynamic factors.

2.4.1. Moisture and Energy Convergence into the Arctic

Global circulation can impact the Arctic temperature field by regulating the transport of energy and moisture into the Arctic. Along with the energy convergence into the Arctic, we calculated the moisture convergence into the Arctic to quantify available precipitable water which is the difference between precipitation and evaporation over the region.

Moisture convergence and latent heat convergence into the Arctic is increasing during springtime. Increasing moisture and latent heat convergence can enhance cloud cover to cause enhanced greenhouse warming over the Arctic. The positive radiative forcing due to enhanced downwelling longwave radiation also contributes to increase SAT. Also increasing moisture and cloud cover would have a negative radiative forcing for the shading effect on the incoming shortwave solar radiation and thus a cooling effect on the SAT field over this region. The following figures show, moisture transport into the Arctic across 60°N latitude (Figure 2.5) and latent heat transport into the Arctic across 60°N latitude (Figure 2.6) are increasing during the mid-March to mid-April period.

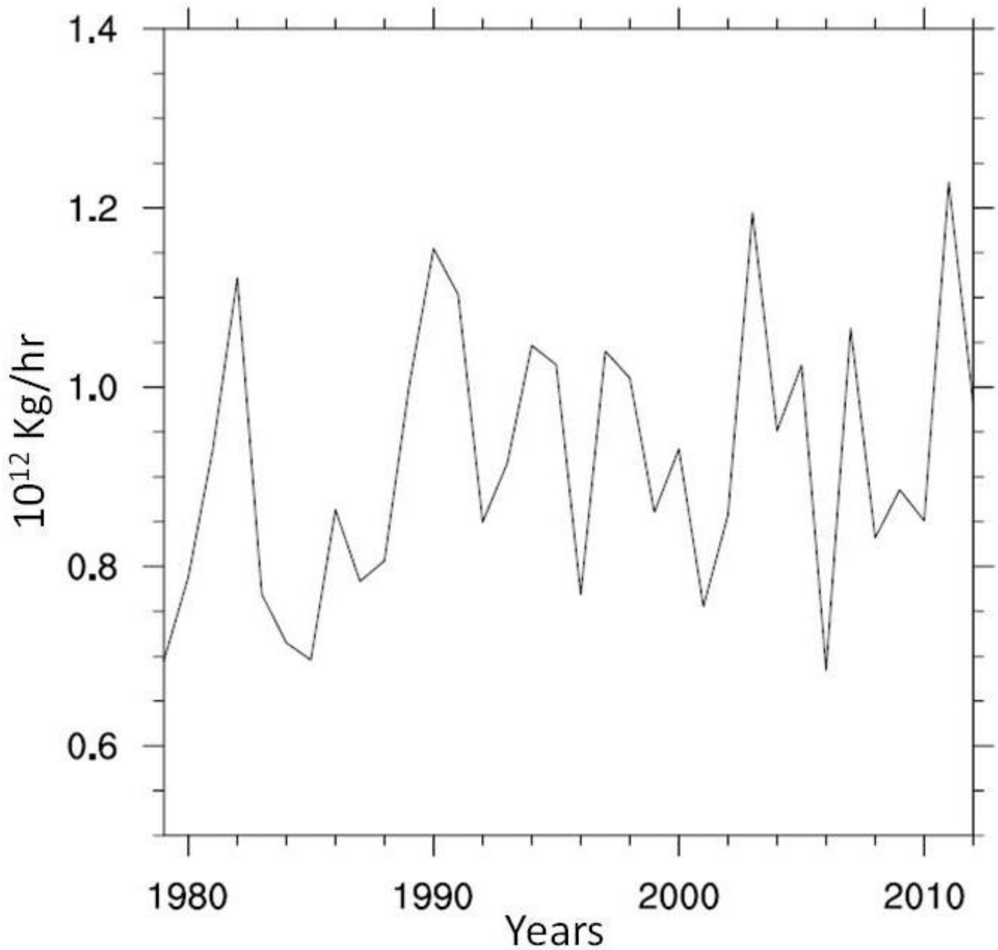

Figure 2.5: Timeseries for moisture transport (in 10^{12} kg/hr) for mid-March to mid-April shows the moisture convergence into the Arctic is increasing over time during 1979-2012 period.

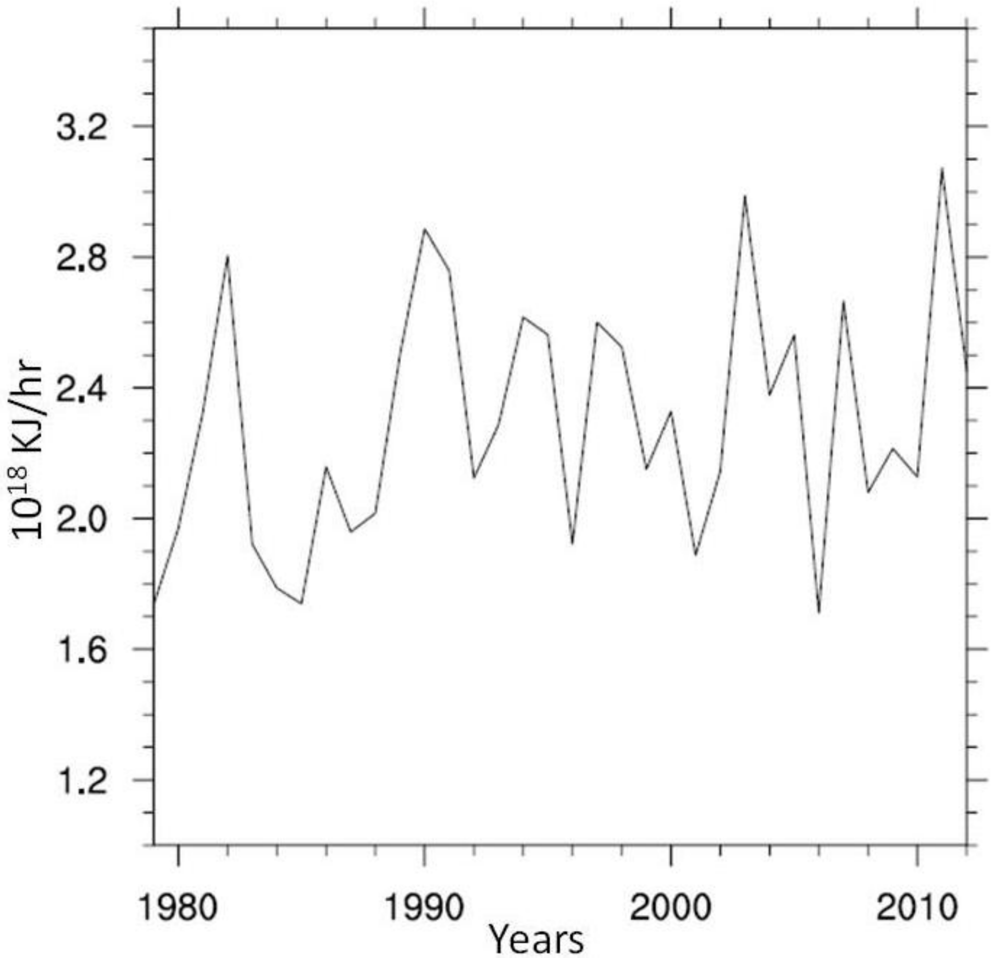

Figure 2.6: Timeseries for latent heat transport (in 10^{18} KJ/hr) for mid-March to mid-April shows latent heat convergence into the Arctic is increasing over time during 1979-2012 period.

The convergence of enthalpy and potential energy is analyzed to study the influence of dry static energy transport into the Arctic during the spring transition period. Potential energy transport into the Arctic across 60°N latitude during mid-March to mid-April period has decreased in recent years (Figure 2.7).

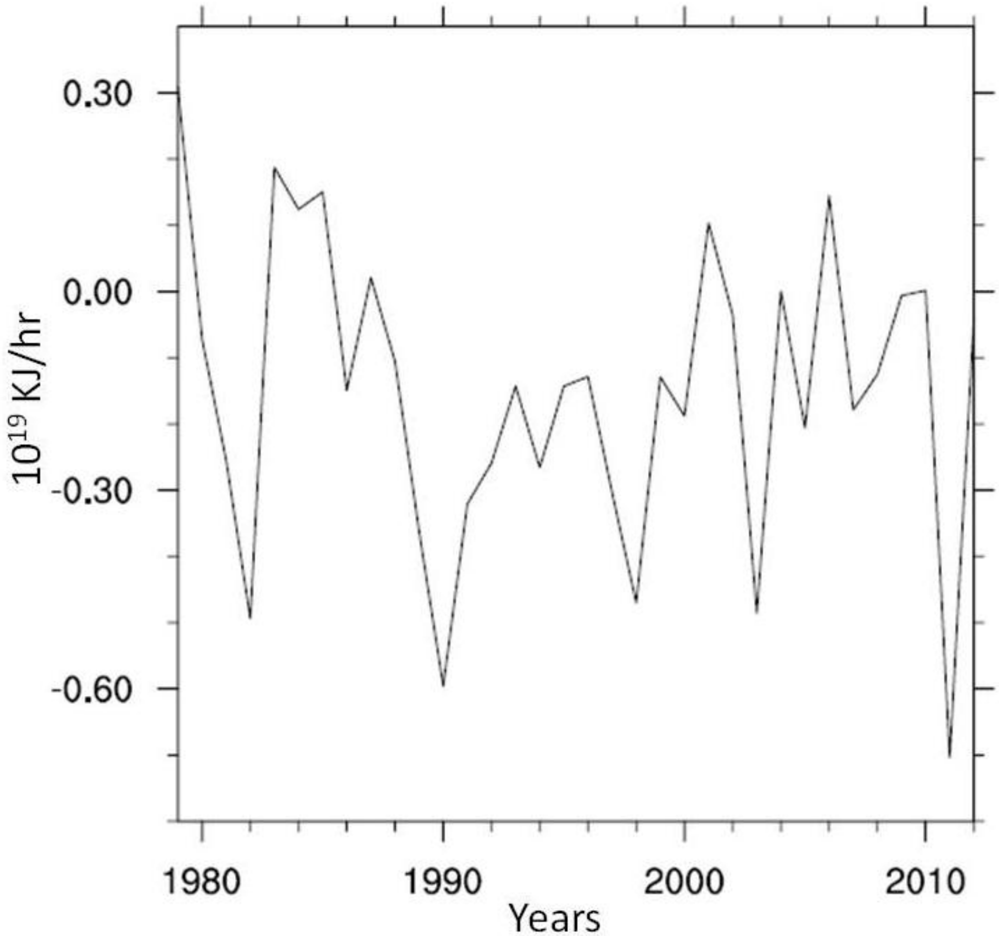

Figure 2.7: Time series for potential energy transport (in 10^{19} KJ/hr) for mid-March to mid-April shows potential energy convergence into the Arctic is decreasing over time during 1979-2012 period.

While for the same period the enthalpy transport into the Arctic is mostly increasing, comparatively less transport occurs around 1995-2005 (Figure 2.8).

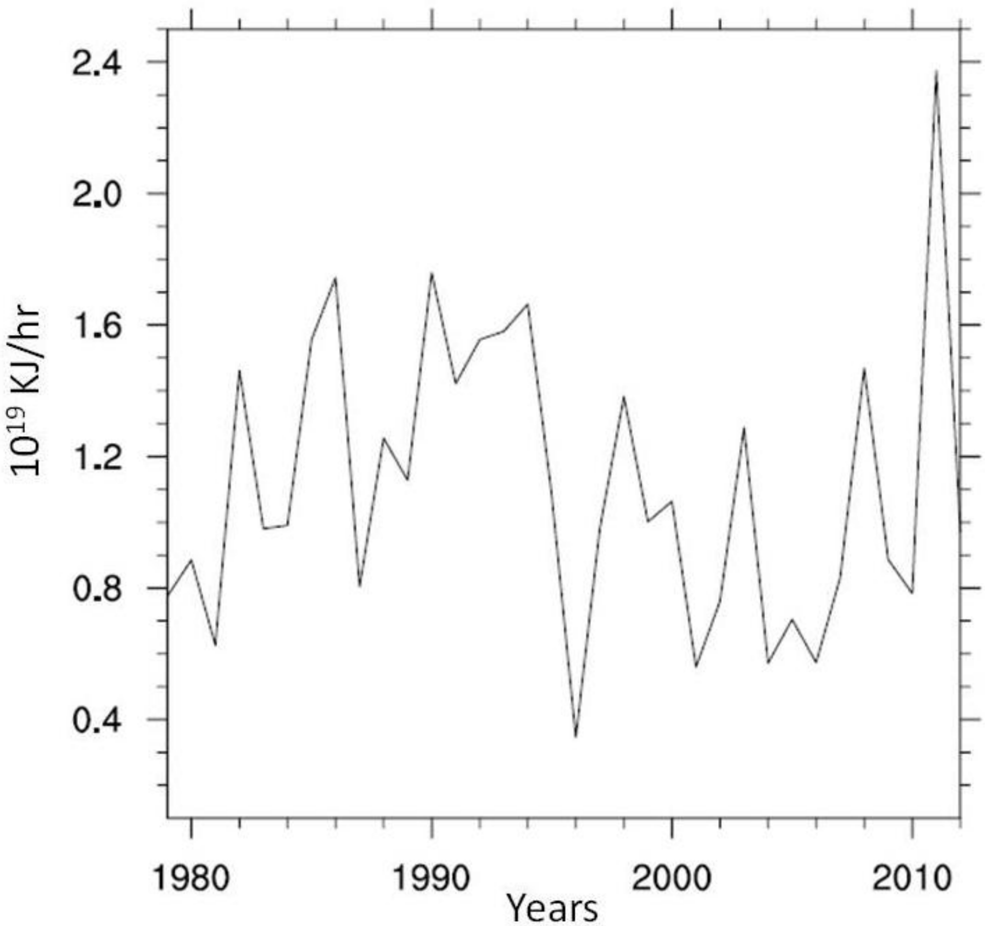

Figure 2.8: Time series for enthalpy transport (in 10^{19}KJ/hr) for mid-March to mid-April shows enthalpy convergence into the Arctic is increasing over time during 1979-2012 period.

The sum of enthalpy and potential energy transport for mid-March to mid-April gives dry static energy (DSE) transport across 60° N latitude into the Arctic. It decreased value seen around 2000-2005 but displays higher value in recent years (Figure 2.9).

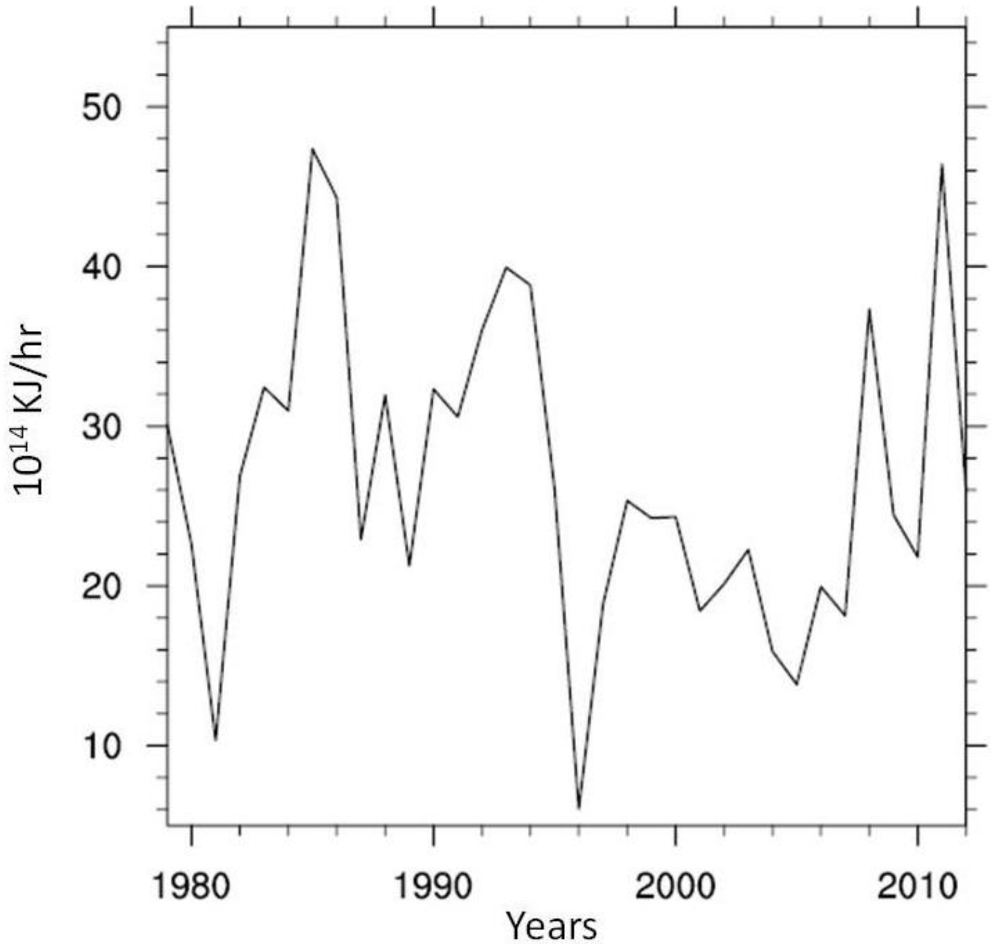

Figure 2.9: Time series for dry static energy transport (in 10^{14} KJ/hr) for mid-March to mid-April shows dry static energy convergence into the Arctic is increasing in recent years.

An increase in dry static energy transport would enhance the convergence of sensible heat into the Arctic that would increase SAT. But a decreased poleward temperature gradient can decrease in poleward sensible heat transport over certain years i.e. around the year 2000. This reduced meridional temperature gradient is supported by the decrease in meridional geopotential height (GPH) gradient. This is a result of the prevailing positive phases in the Arctic Oscillation (AO) which is an opposing pattern of pressure between the Arctic and the mid-latitudes. The positive AO phase results in lower surface pressure over the Arctic and extends the height of the upper pressure levels. Due to barotropic condition GPH levels also increase leading to a decreased meridional GPH gradient. The time series of 250 hPa level GPH (Figure 2.10) shows the extended height.

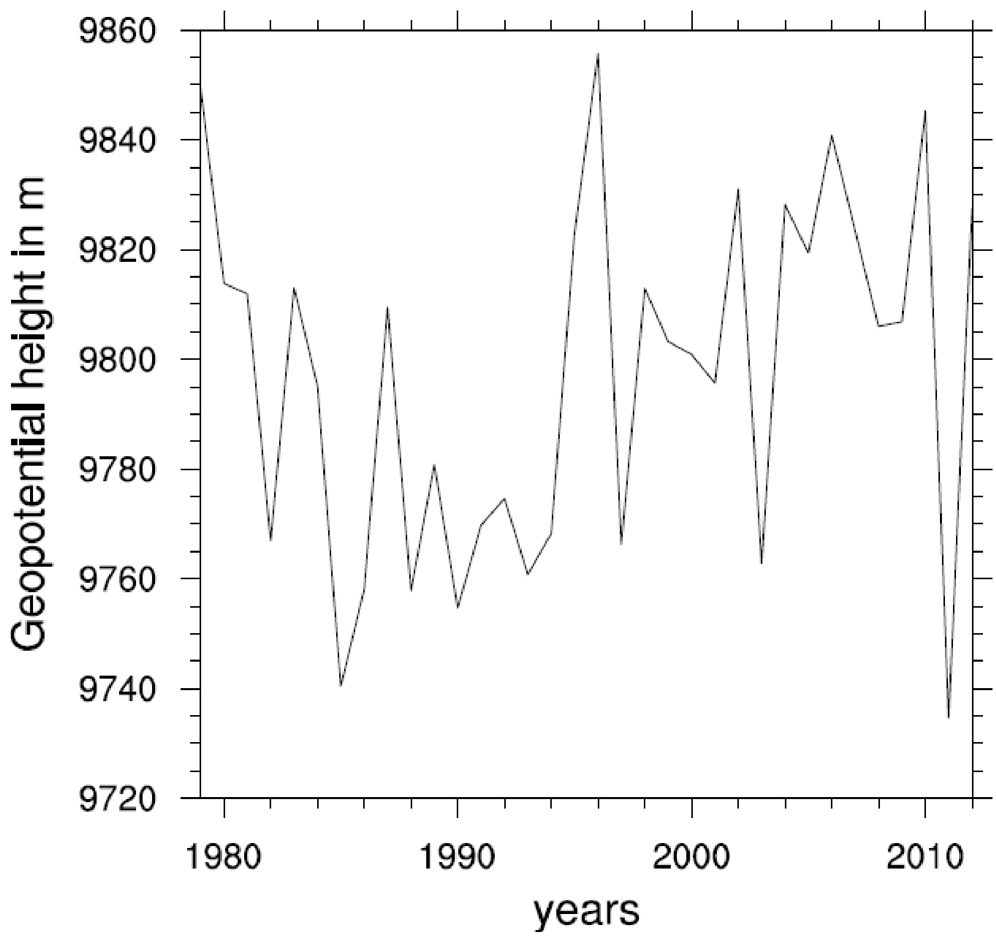

Figure 2.10: Timeseries of 250 hpa geopotential height (in m) shows extended height during 1995-2000 supporting reduced meridional GPH gradient.

The time series of 500 hPa level GPH (Figure 2.11) also supports the extended height of GPH and thus pressure levels.

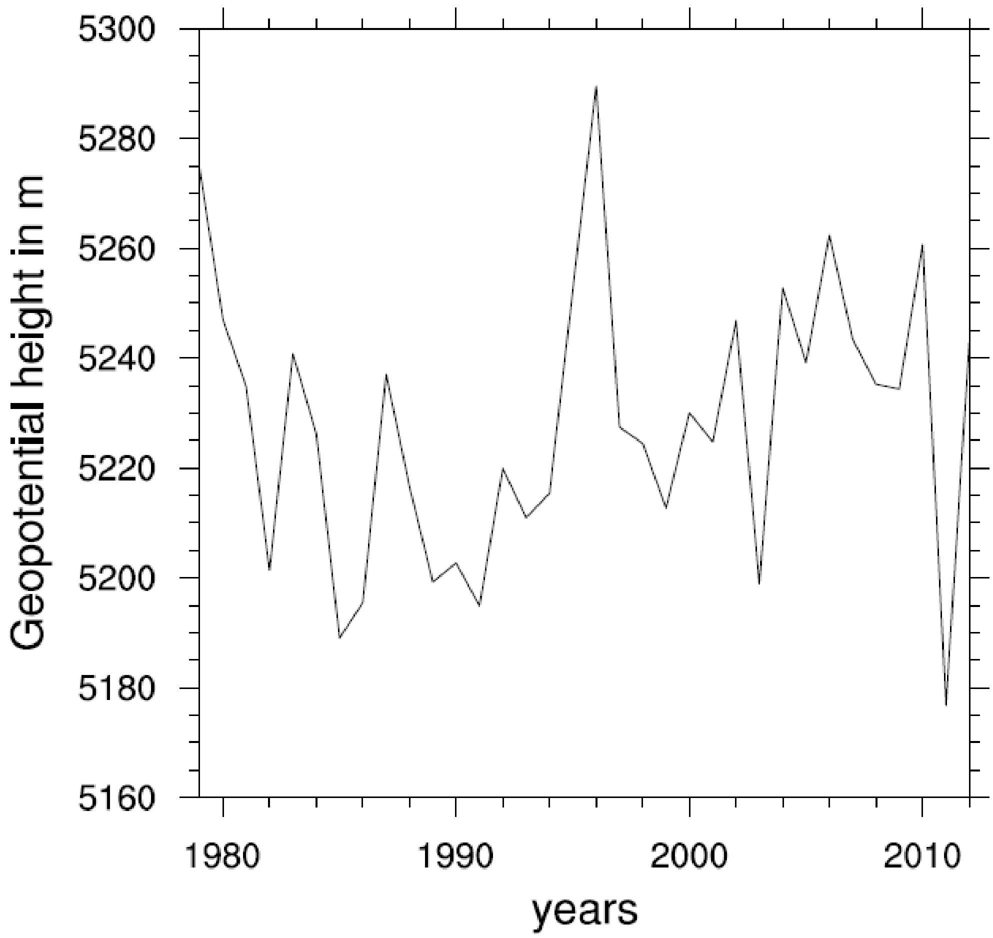

Figure 2.11: Timeseries of 500 hpa geopotential height (in m) shows extended height during 1995-2000 period supporting reduced meridional GPH gradient.

As a result of an extended GPH, the meridional GPH gradient decreased, causing a reduced meridional temperature gradient. This results in reduced poleward sensible heat transport and a dip in the DSE transport time series. Large latent heat energy inflow during mid-March to mid-April compensates for the decrease in DSE to a large extent and an increase in moist static energy (MSE) transport into the Arctic (Figure 2.12) is seen.

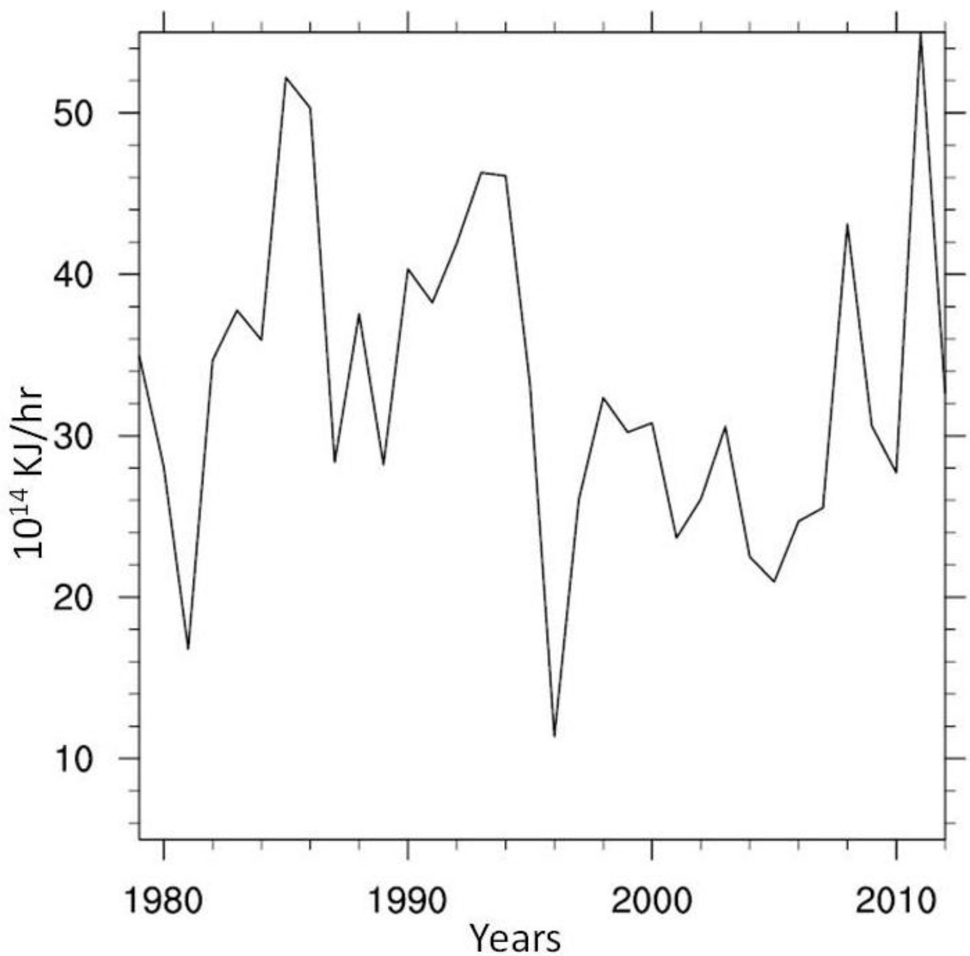

Figure 2.12: Timeseries for transport of moist static energy into Arctic (in 10^{14} KJ/hr) for mid-March to mid-April shows an increase in moist static energy convergence into the Arctic in recent years.

This increased transport of energy into the Arctic acts to increase the surface energy budget and SAT over the Arctic. So, the inflow of moisture and energy from the mid-latitudes into the Arctic has increased over the study period. This large scale transport can in turn impact the regional thermodynamic processes over the Arctic.

2.4.2. Radiative and Turbulent Heat Fluxes for Surface Energy Budget:

With increased moisture and energy transport into the Arctic, atmospheric dynamics can critically modulate the surface heat budget by impacting radiative and turbulent heat fluxes over the Arctic. For example an increase in warm and moist air transport into the Arctic causes enhanced downwelling longwave and turbulent heat flux to influence the extreme ice loss event in 2007 (Graversen et al. 2011). The study of longwave radiation budget, shortwave radiation budget and cloudiness reveals the influence of regional thermodynamics to regulate the total surface energy budget and thus the SAT.

Enhanced moisture and latent heat convergence into the Arctic can increase the cloudiness. Understanding the evolution of cloudiness over the Arctic is important for studying climate system for its complex interaction with atmospheric dynamics and the radiation budget (Curry et al. 1996). Consistent with increased advection of moisture and latent heat into the Arctic, the cloud cover during the springtime is increasing over the Arctic. This increase in cloudiness in spring over the Arctic can lead to surface warming through an enhanced greenhouse effect but it can also cool the surface by reducing incoming solar radiation. Comparing the cloud cover anomaly to the long term climatology (1979-2012) shows a remarkable positive anomaly over the Arctic for last decade of our study (Figure 2.13).

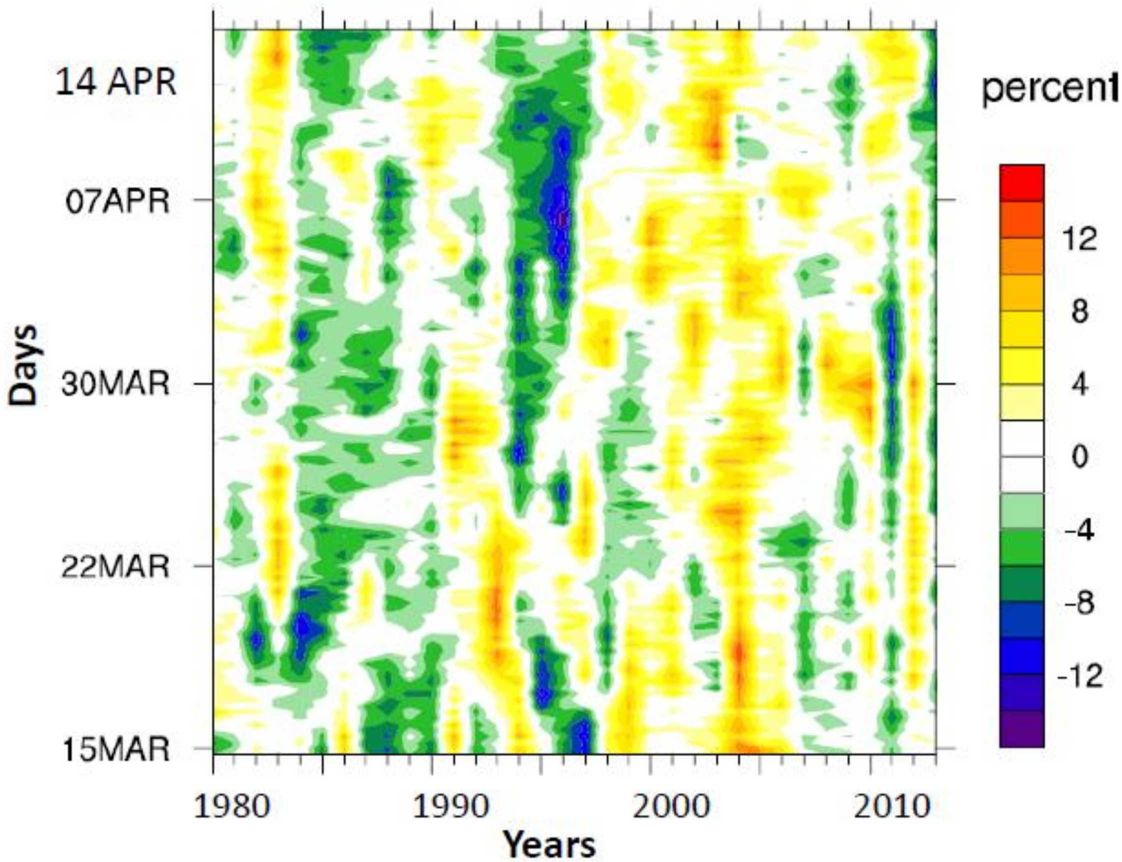

Figure 2.13: Total cloud cover anomaly over the Arctic, compared to long term climatology (1979-2012) shows a positive anomaly for the last decade of the study. The increased cloudiness impacts the net radiation budget at surface.

The increasing spring cloud cover has a robust positive radiative forcing on the surface energy budget by enhancing the downwelling longwave radiation flux. The upwelling longwave terrestrial radiation is trapped by the clouds causing an increase in downwelling longwave radiation reaching to the ground due to an enhanced greenhouse effect (Figure 2.14).

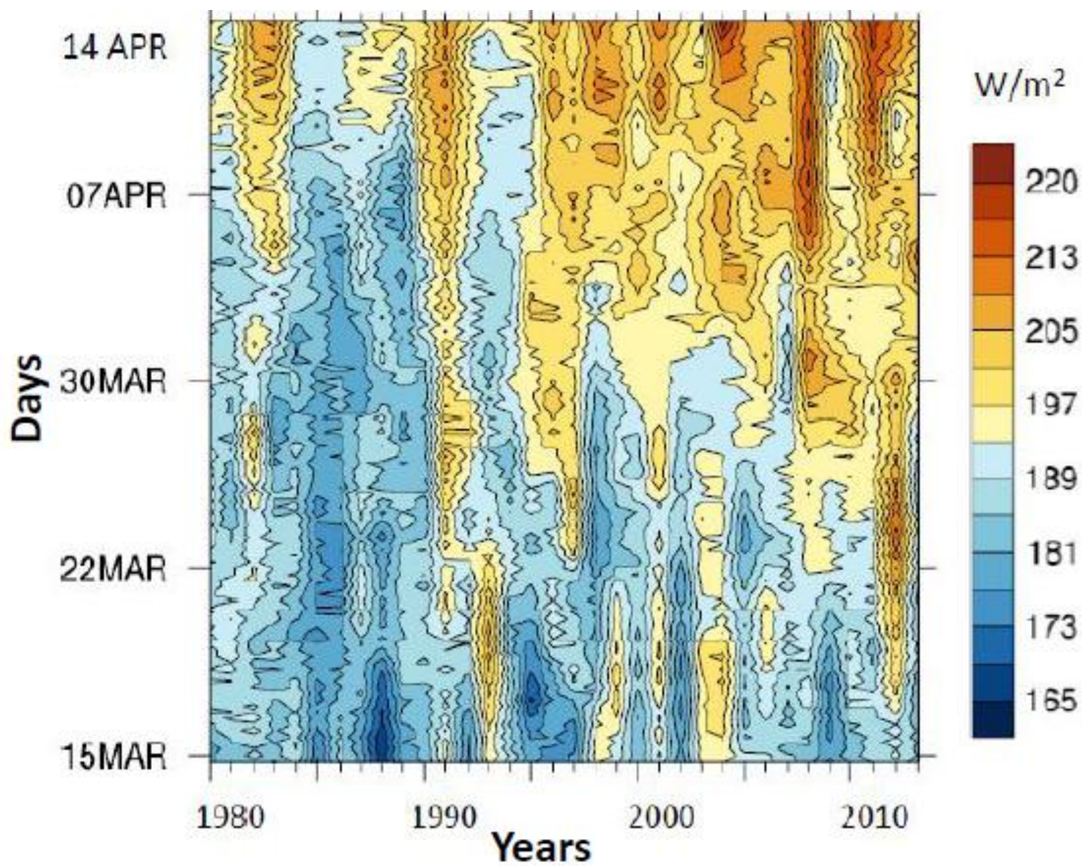

Figure 2.14: Time series for downwelling longwave radiation flux (in W/m^2) during mid-March to mid-April period shows an increased downwelling longwave radiation reaching to the ground due to enhanced greenhouse effect.

In recent years the increase in downward longwave radiation has shifted to an earlier time. The anomalous downwelling longwave radiation displays a prominent positive anomaly in the last decade of our study which is consistent with the positive cloud cover anomaly for the same time period (Figure 2.15).

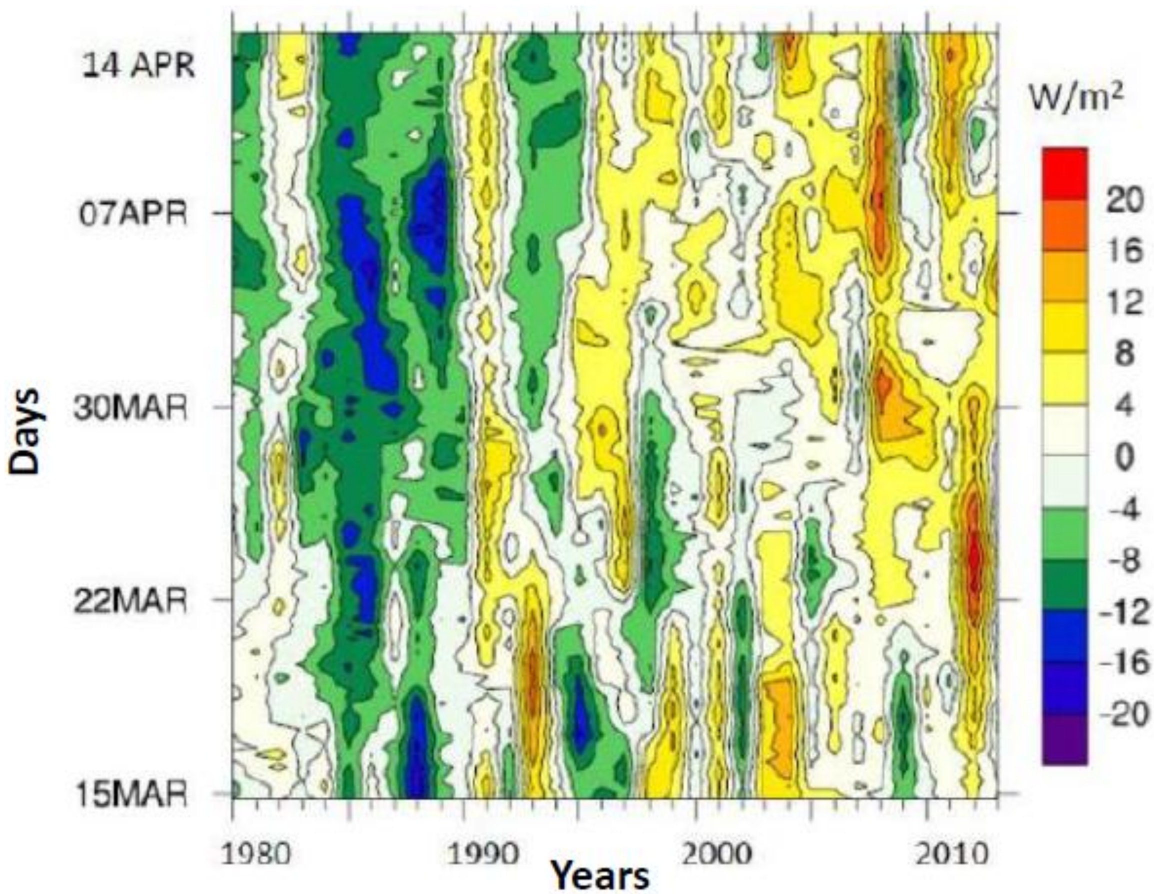

Figure 2.15: Positive anomaly in downwelling longwave radiation (in W/m^2) during mid-March to mid-April compared to long term climatology (2979-2012) is consistent with anomalous cloudiness during the same period.

Increased cloud cover can reflect additional incoming solar radiation to space. This decrease in incoming shortwave radiation due to cloud cover would have a cooling effect to the surface energy budget. The shading effect of clouds on the incoming shortwave radiation has decreased over time (Figure 2.16).

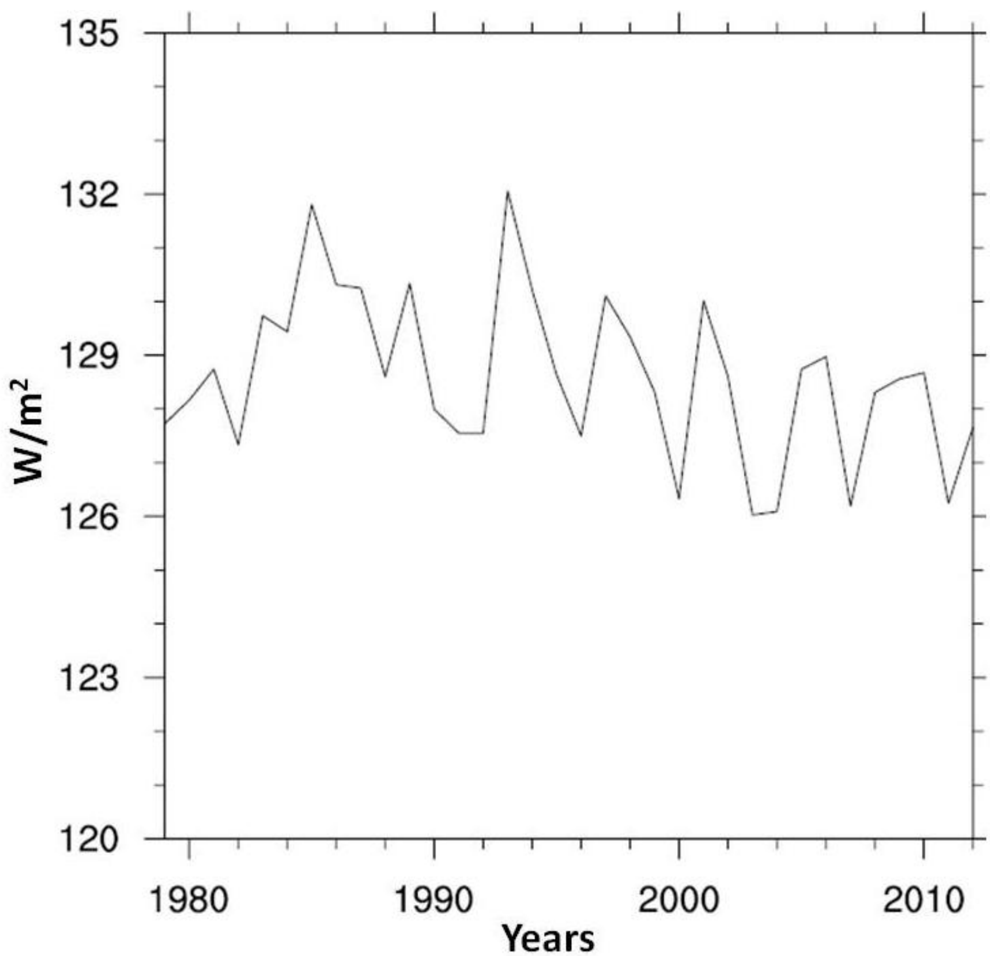

Figure 2.16: Timeseries of downwelling shortwave radiation flux (in W/m^2) for mid-March to mid-April shows a decrease in incoming solar radiation during 1979-2012 period due to shading effect of enhanced cloudiness.

According to Kirchhoff's law of thermal radiation, outgoing terrestrial radiation increases with elevated surface temperature. This has a cooling effect to the surface energy budget. The spring increase in upwelling longwave radiation is consistent with previous analysis (Figure 2.17).

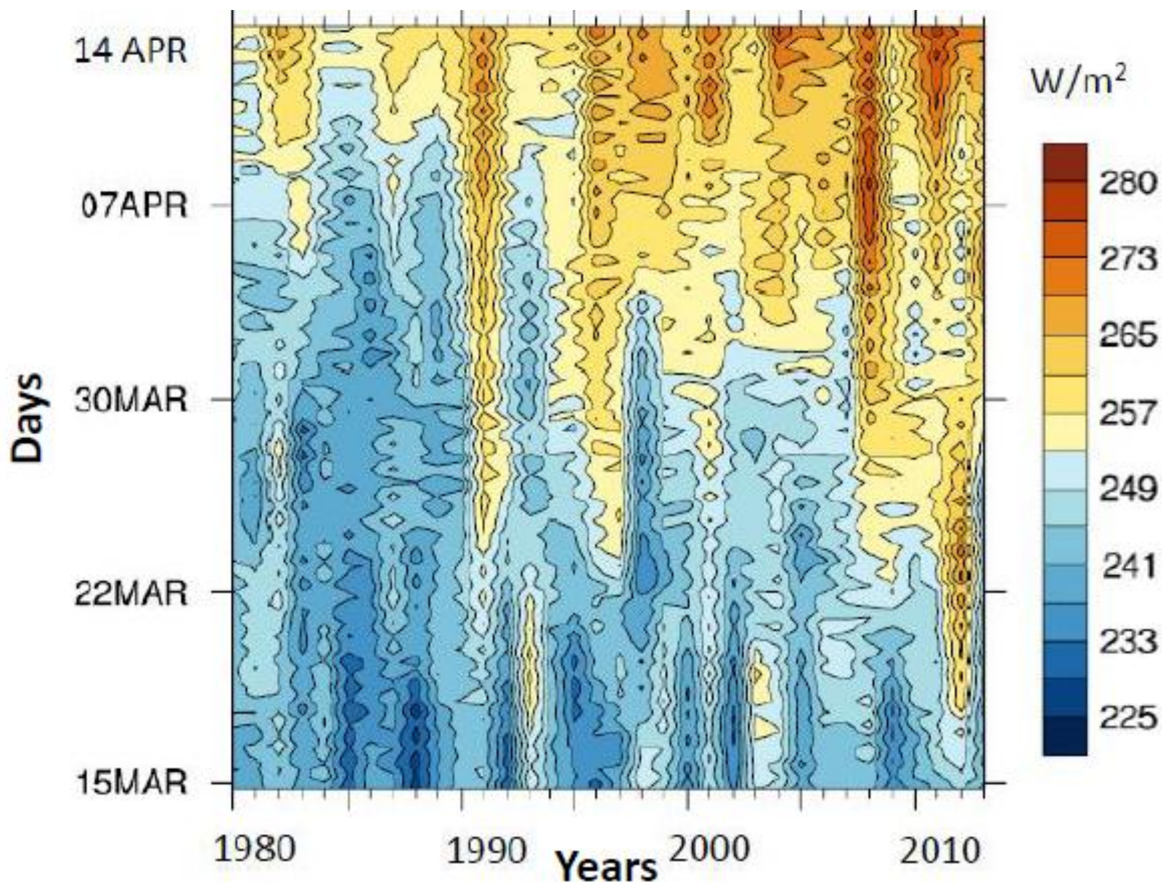

Figure 2.17: Timeseries for upwelling longwave radiation flux (in W/m^2) during mid-March to mid-April period is consistent with increase in SAT during 1979-2012 period.

As the Arctic remains snow covered for a considerable period of the year, the surface albedo plays an important role in regulating the surface radiation budget. Sea ice and snow cover have a high surface albedo that reflect back a great amount of incident solar radiation to space. But with the earlier retreat in sea ice over the Arctic Ocean, the sea ice is getting reduced. The area averaged Sea ice concentration over the Arctic is decreasing over time (Figure 2.18).

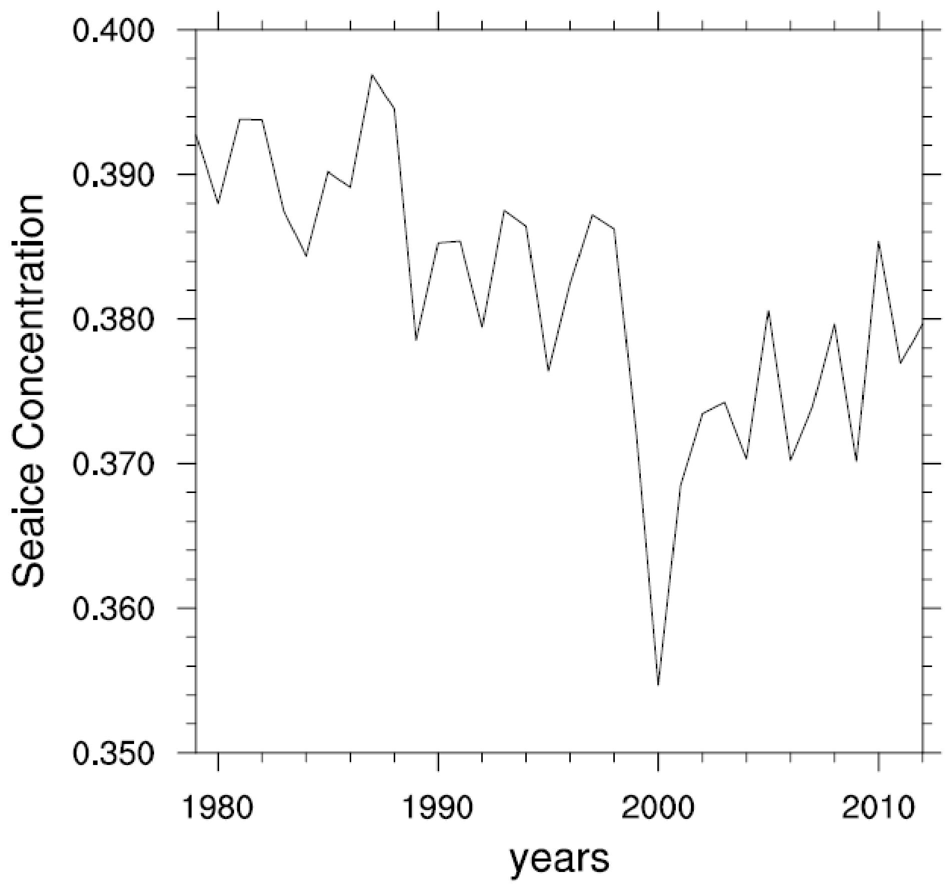

Figure 2.18: Area averaged sea ice concentration over the Arctic is decreasing over time. The sea ice concentration values are comparatively lower as averaging over the area north of 60°N has included lower values at edges of the Arctic.

The reduced sea ice cover would decrease the surface albedo. This would in turn result in reduced outgoing shortwave radiation (Figure 2.19) increasing the surface energy budget and warming process.

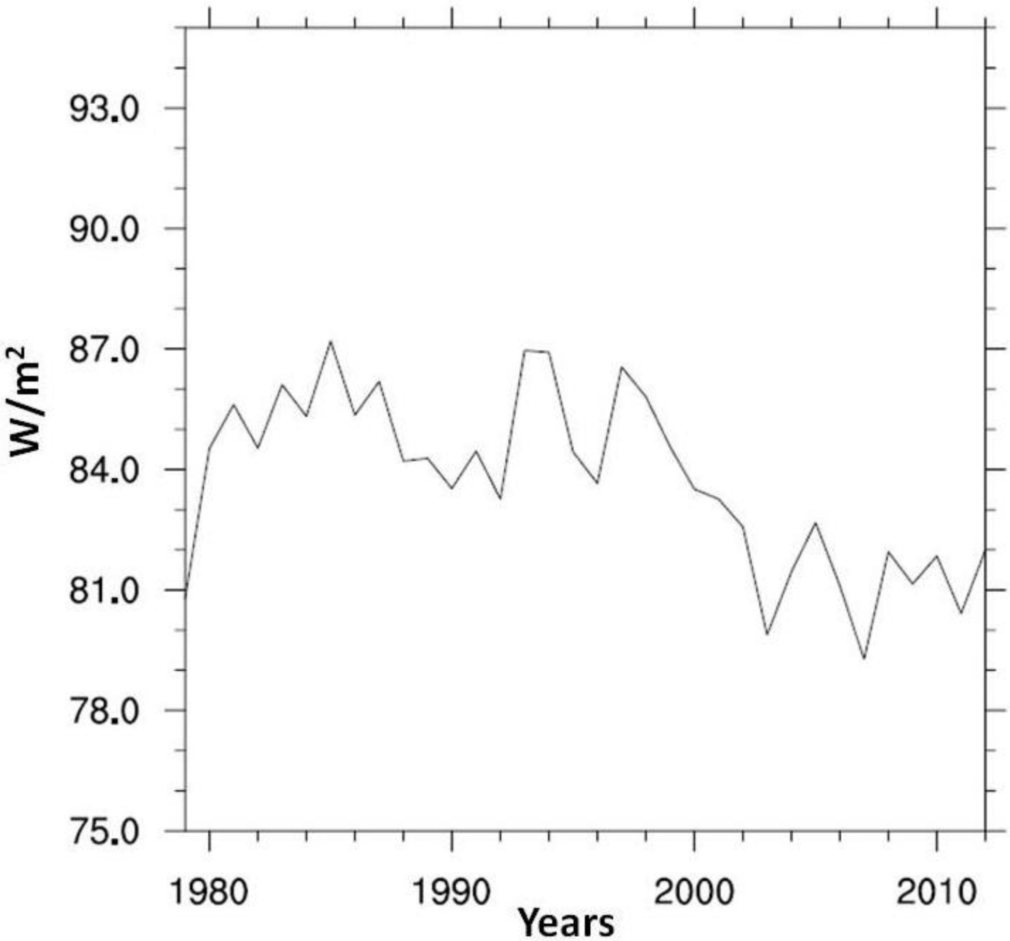

Figure 2.19: Upwelling shortwave radiation flux (in W/m^2) is decreasing over time as a consequence of less surface albedo due to reduced sea ice.

Comparing the values for radiation fluxes at surface shows that downwelling longwave radiation is a dominant term in the net radiation budget over the Arctic compared to downwelling shortwave radiation. The enhanced downwelling longwave radiation and positive surface albedo forcing compensates for cooling from reduced downwelling shortwave radiation and the increase in outgoing longwave radiation flux. There is an overall positive anomaly in the net downward radiation flux at surface during the last decade of the study period (Figure 2.20).

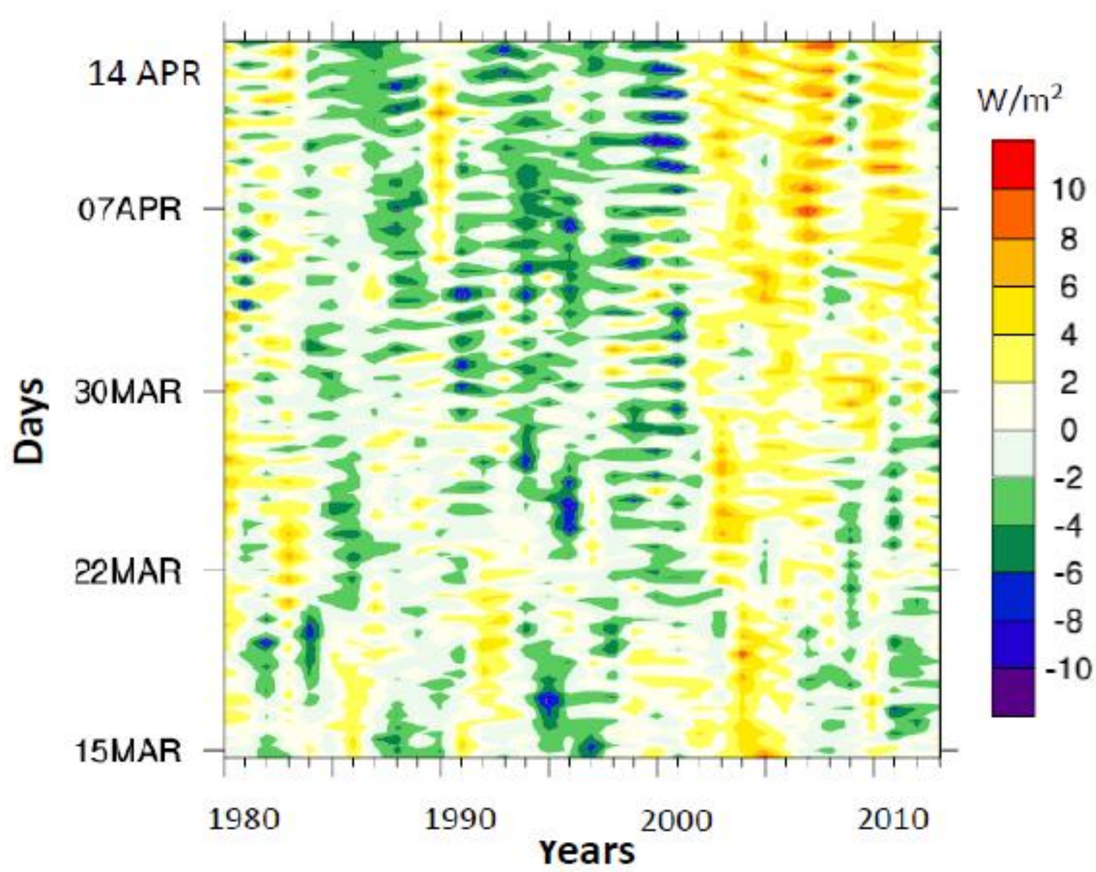

Figure 2.20: Positive anomaly in net radiation flux (in W/m^2) during the last decade of the study provides extra energy for the surface energy budget to enhance warming.

The complex interaction of different feedback mechanisms due to cloudiness, moisture convergence and surface albedo impacts the surface radiation budget of Arctic. We wanted to focus in our study on whether dynamical and physical changes over the Arctic are providing extra energy for warming. More available radiative energy flux can influence the surface energy budget to enhance the warming. The sensible and latent heat fluxes play an important role in regulating the surface energy budget also. The increase in downward sensible heat flux (Figure 2.21) is consistent with the Arctic warming trend.

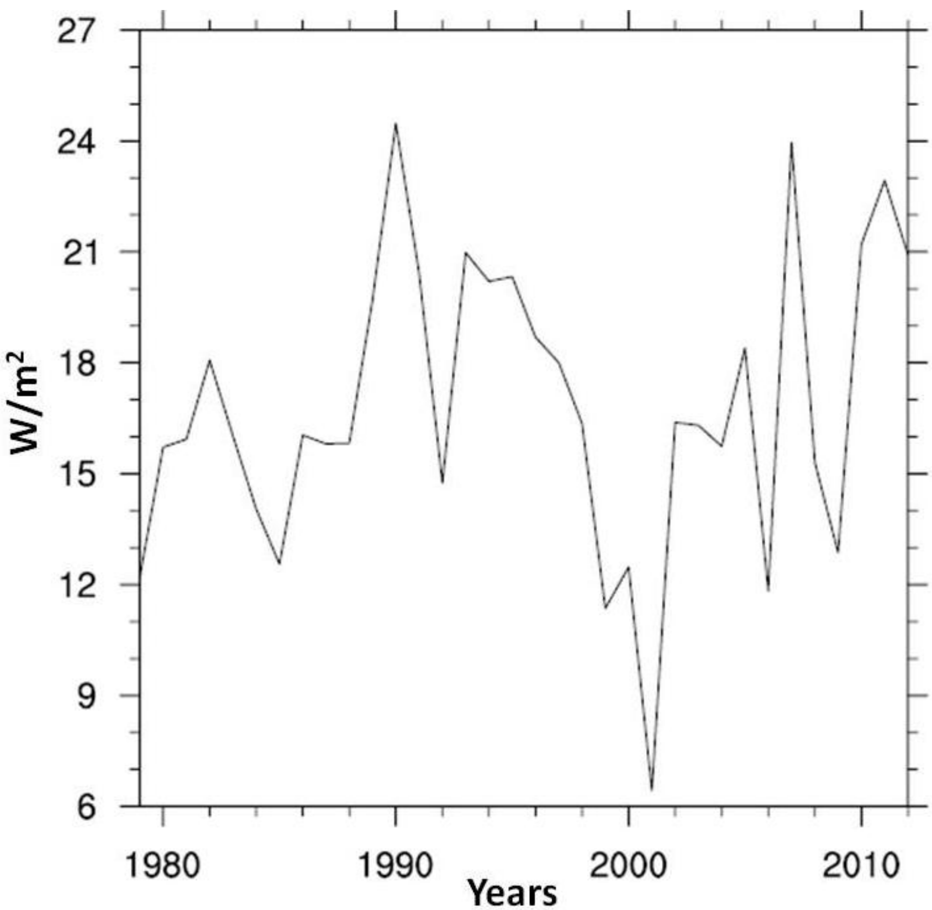

Figure 2.21: Increase in downward sensible heat flux (in W/m^2) over time is consistent with the warming trend over the Arctic.

With enhanced warm air advection from lower latitude, the atmosphere over the Arctic is getting warmer. Due to downward temperature gradient between warmer atmosphere and the surface the downward sensible heat flux has increased over the study period. The warmer atmosphere acts as a heat source to impact the surface energy budget through enhanced downward sensible heat flux. But the latent heat flux trends lead to surface cooling since the downward latent heat flux is decreasing (Figure 2.22).

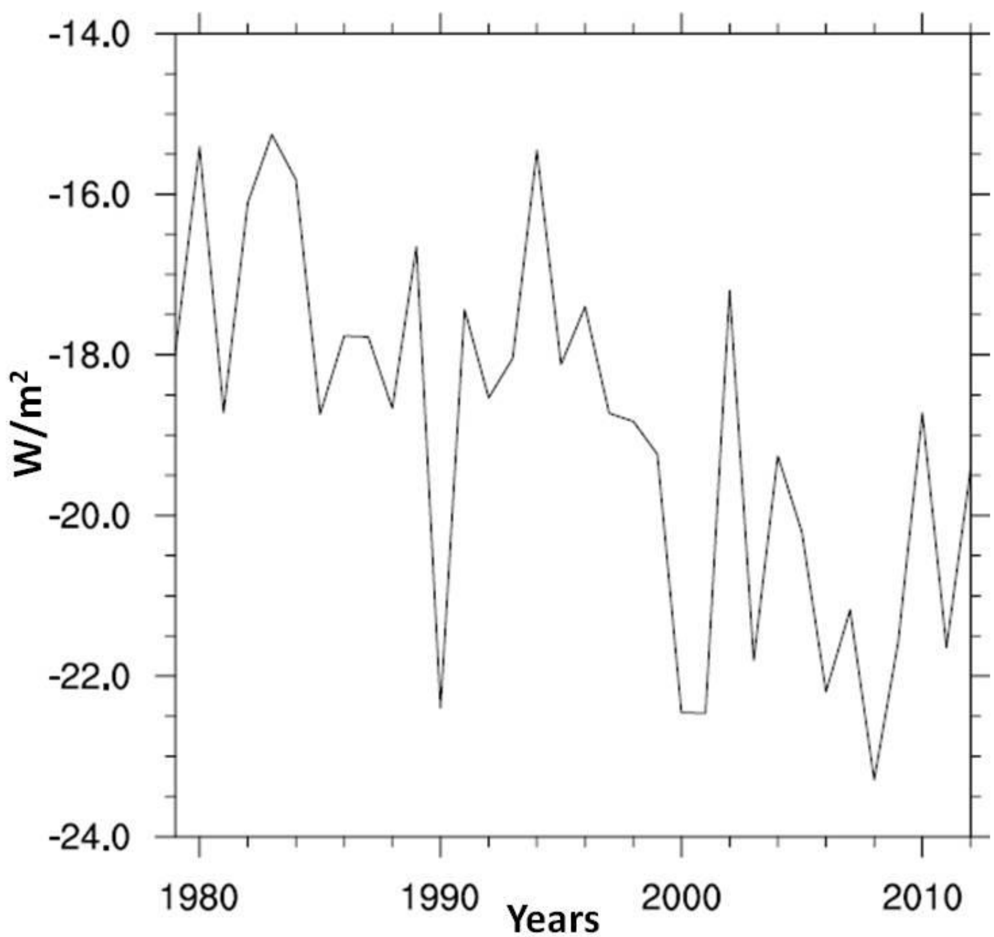

Figure 2.22: Decrease in downward latent heat flux (in W/m^2) trends lead to surface cooling over the Arctic during the study period.

Due to an earlier sea ice retreat there is more open water available for evaporation from resulting in an enhanced exchange of upward latent heat flux from ground to atmosphere. This will reduce the contribution of downward latent heat flux to the surface energy budget associated with negative anomaly in downward latent heat flux compared to long term climatology for the last decade of our study (Figure 2.23)

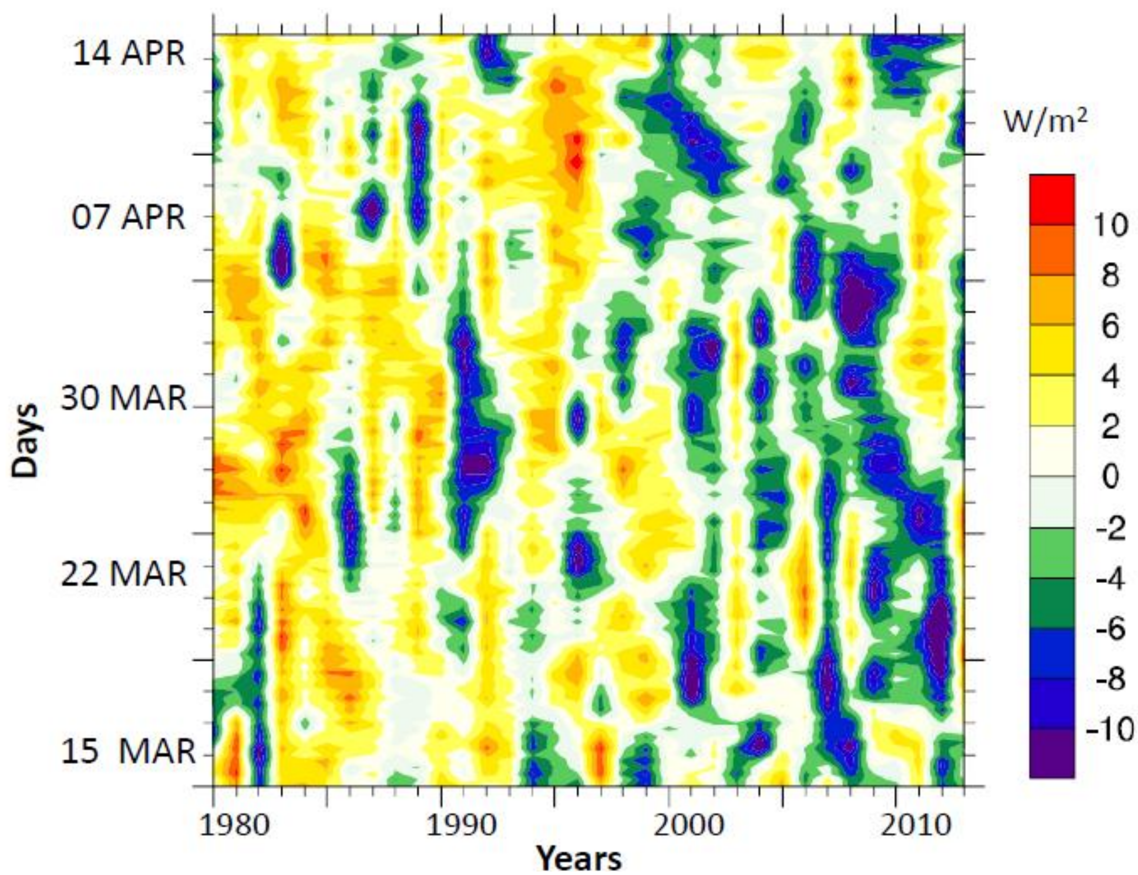

Figure 2.23: Change in downward latent heat flux (in W/m^2) anomaly compared to long term climatology during mid-March to mid-April period.

The advection of moisture into the Arctic can impact the vapor pressure gradient to lower the evaporation rate. But the evaporation also depends on the stability and wind speed. It has been reported increased wind speed over the Arctic that can also influence in enhanced evaporation (Stegall and Zhang 2012)

2.4.3. Contribution of Dynamic and Thermodynamic Factors for Shaping the Spring Transition Climatology in Warming Climate

Energy and moisture inflow from mid-latitudes into the Arctic as well as the complex feedback and interaction between radiative and turbulent heat fluxes play a key role in regulating the arctic surface energy budget and trend in SAT. For a better understanding of the contributing physical factors in shaping the spring transition as seen through surface warming, we examined changes in different dynamic and thermodynamic factors over the Arctic.

The dynamic factors such as transport of moisture and energy can influence the local thermodynamic feedback processes. An increase in moisture and latent heat transport into the Arctic from mid-latitudes over time results in enhanced cloudiness during springtime. Enhanced total cloud cover over the Arctic increases downwelling longwave radiation and contributes to surface warming by the enhanced greenhouse effect. The increase in cloudiness can reduce downwelling incoming shortwave radiation flux at the surface by reflecting back some part of the incoming solar radiation to space again. Thus increase in total cloud cover has a negative feedback to the surface energy budget as well.

Surface Albedo is another crucial factor that impacts the net surface radiation balance. The retreat in sea ice decreases the surface albedo over the Arctic. This leads to a positive feedback reducing upwelling shortwave radiation flux and warming the surface further. The retreat in sea ice and thus the shortwave radiation budget during spring is influenced by an enhanced greenhouse effect through increased cloudiness and an enhanced sensible heat flux from a warmer atmosphere. The overall net downwelling radiation flux has increased in recent years, providing extra energy warming the surface.

Sensible heat transport into Arctic also contributes to warming though the influence is not consistent throughout the period of study. A decreased poleward temperature gradient associated with an increased GPH during the positive phase of the Arctic Oscillation causes reduced sensible heat transport into the Arctic in certain years.

Exchange of turbulent heat fluxes is also important for the surface energy budget. The warm air advection into the Arctic leads to a warmer atmosphere over Arctic resulting in an enhanced downward temperature gradient between atmosphere and surface. The increase in the sensible heat flux from atmosphere to ground provides considerable energy for the warming. But the decrease in downward latent heat flux during the period of study leads in surface cooling. Enhanced sea ice retreat results in more open sea water and warmer SATs which increases evaporation and reduces downward latent heat flux.

In short, the most important factors in shaping the surface warming during the spring transition period are enhanced downwelling longwave radiation flux from the increase in cloudiness due to more moisture and latent heat convergence in the Arctic. The increase in sensible heat flux associated with warm air advection and enhanced absorption of shortwave radiation at surface plays an important role in warming. Dry static energy transport from lower latitudes has contribution in the surface energy budget as well.

Correlation analysis helps to quantify the importance of the contributing physical factors in surface warming with the contributing physical factors. The longwave downwelling radiation flux has the highest correlation of 0.91 with SAT, followed by 0.75 for enthalpy convergence, 0.6 for moisture convergence, 0.6 for upwelling shortwave radiation flux, 0.55 for sensible heat flux and 0.5 with sea ice. This proves the most important role of downwelling longwave radiation flux due to enhanced greenhouse effect to regulate the surface warming during the spring transition period.

Chapter 3 Causes of Interannual Variability in Arctic Springtime Transition

3.1. Introduction

From analysis of SAT time series in the previous chapter, it is clear that interannual variability is prominent. This chapter explores the physical parameters causing the interannual variability of the SAT. A spatial analysis is conducted over the Arctic for a better understanding of the regional importance of different physical parameters that contribute to the warming process.

3.2. Employed Method:

To study the spatial distribution of energy and moisture budget in warmer or colder SAT years we performed composite analysis study for various physical parameters during springtime. For the composite analysis, we used the same dataset and calculation approach employed in the previous chapter to analyze the attributing dynamic and thermodynamic parameters in regulating the spring climatology.

The composite analysis study is focusing the whole Arctic i.e. poleward from 60°N latitude and the mid-latitude region from 40°N to 60°N latitude. We included the mid-latitude region in our study to examine the linkage of large scale atmospheric dynamics on the regional physical processes over the Arctic. Our area of interest is shown below (Figure 3.1) where the midlatitude region is divided into four sectors: the North Atlantic (70°W–20°E), the North Pacific (140°E–120°W), Eurasia (20°–140°E), and North America (120°–70°W) to investigate the regional importance of different physical parameters:

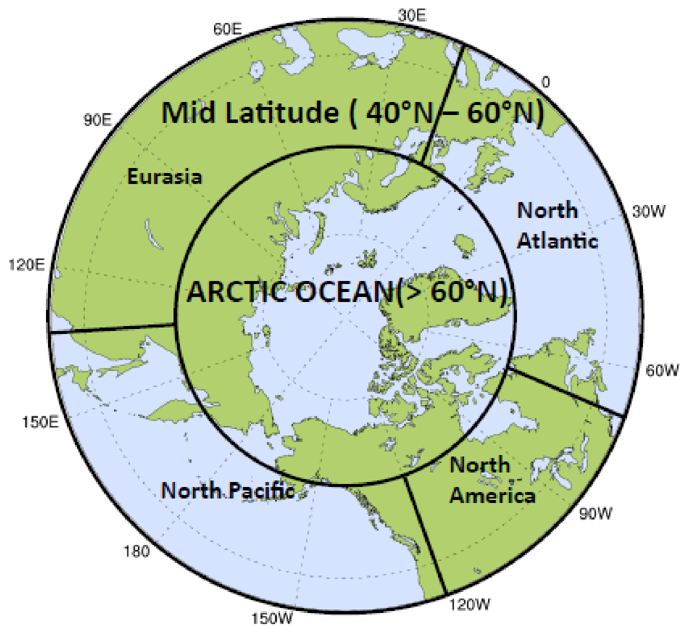

Figure 3.1: The area of interest for the composite analysis is the Arctic (above 60°N) and the mid-latitudes (40° to 60° N). To investigate the regional importance of contributing parameters, the mid-latitudes is divided into North Pacific, North America, North Atlantic and Eurasia.

The SAT time series during mid-March to mid-April from 1979-2012 period shows interannual variability superimposed on an increasing SAT trend. Years that are above or below the 0.5 standard deviations are chosen for the composite analysis (Figure 3.2).

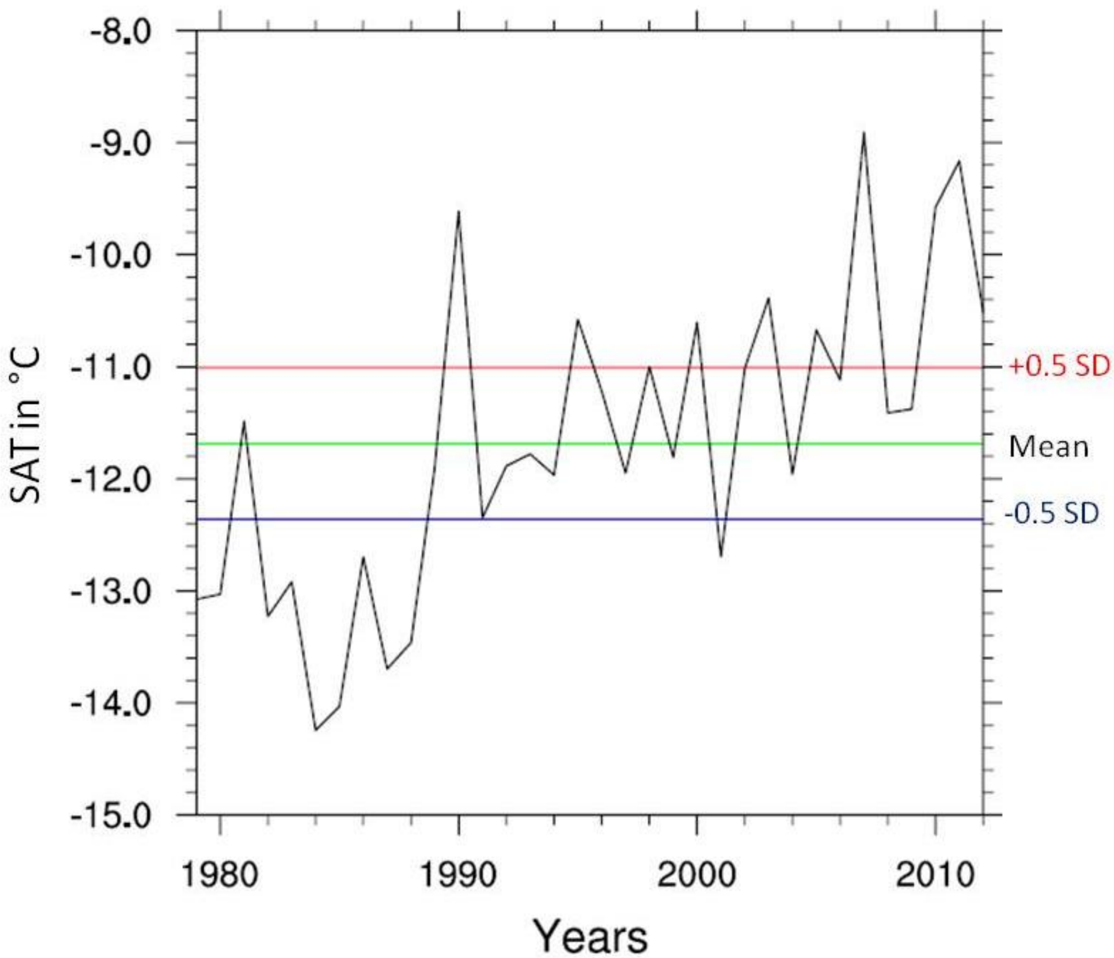

Figure 3.2: Interannual variability is superimposed on the increasing SAT (in °C) for the mid-March to mid-April period during 1979-2012.

The positive and negative phases are composited separately and plotted spatially. The difference between the warm cases and the cold cases results in a spatial distribution of an enhanced warm case Table 3.1 displays the years that comprise the warm and cold cases.

Table 3.1: Warm and cold SAT years during mid-March to mid-April period for composite study.

Warm Years	Cold Years
1990	1979
1995	1980
1998	1982
2000	1983
2003	1984
2005	1985
2007	1986
2010	1987
2011	1988
2012	2001

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We should note that all the warm SAT years occurred after 1990 i.e. during last two decades of the study whereas 9 out of 10 cold SAT years occurred before 1990 i.e. during the first decade of our study. This distribution also reinforces the fact that the Arctic is warming over time associated with warm temperature events during the spring transition period. The following figure shows the map projection used throughout the composite analysis where North Pacific side of the Arctic is at the upper part and the North Atlantic side of the Arctic is at the lower part of the map (Figure 3.3).

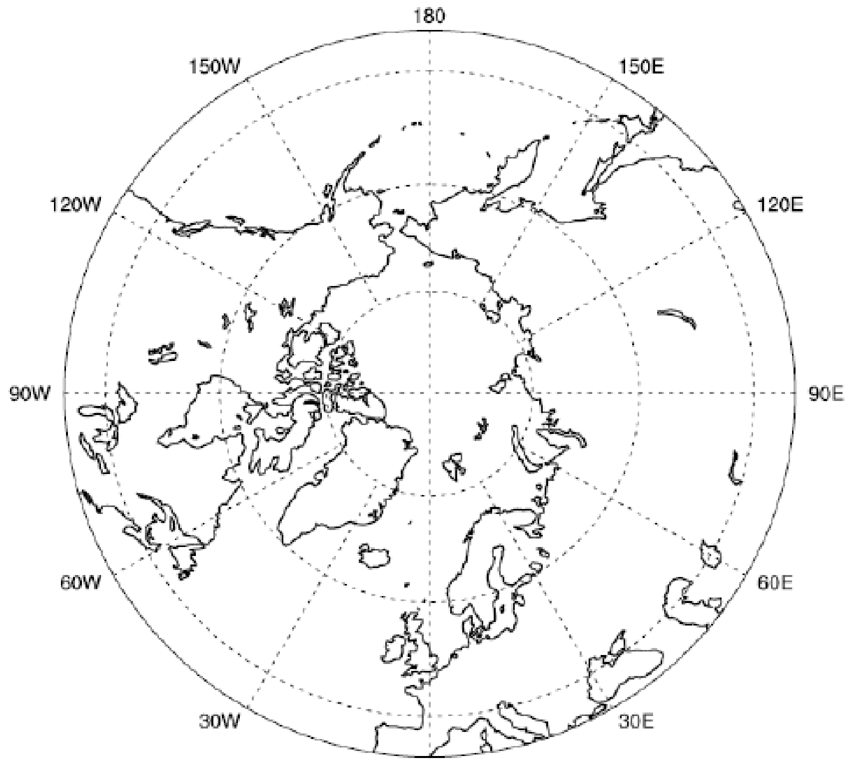

Figure 3.3: The map projection used for the composite analysis.

3.3. Composite Analysis and Corresponding Spatial Distribution for SAT and Contributing Physical Parameters:

While tracking this interannual variability of SAT a composite analysis of warm and cold temperature years reveal the difference in the spatial distribution of warming between positive and negative temperature years for mid-March to mid-April period. An overall warming over the whole Arctic during this particular time period is revealed with anomalously high SAT over the Eurasia, Alaska, northern Canada and part of Greenland (Figure 3.4).

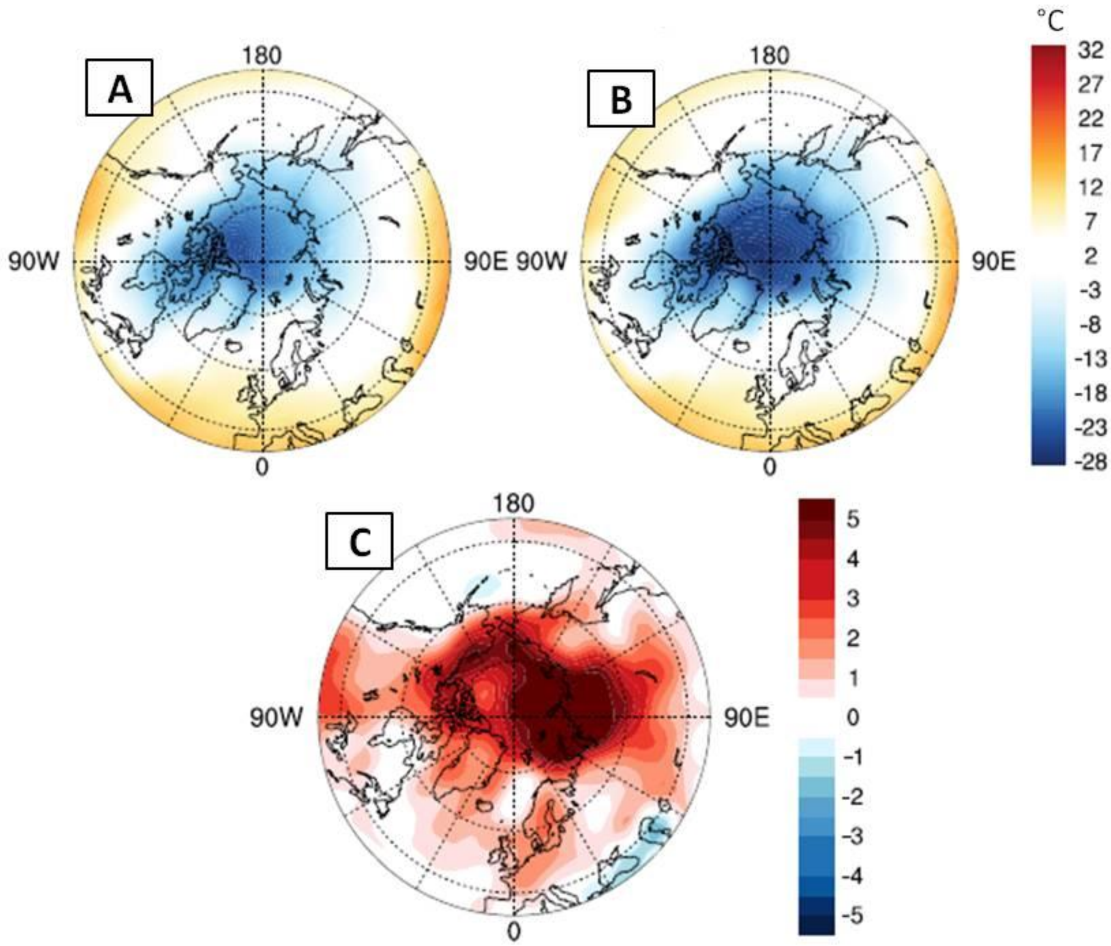

Figure 3.4: Spatial distribution of SAT with shaded contours representing SAT (in °C) due to corresponding composite analysis for (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

In the next section, we present the regional patterns of the physical parameters that contribute to warming over the Arctic.

3.3.1 Linkage with Large Scale Atmospheric Circulation:

The difference in atmospheric circulation patterns in between warm and cool years can explain how increased energy and moisture transport into the Arctic can impact the Arctic SATs. Composite analysis for moisture and latent heat transport are compared for warm and cool years to determine the impact of this dynamic factor in regulating total cloud cover, shortwave and longwave radiation budget.

The moisture convergence during warm SAT years occurs over all of the North Pacific, North Atlantic side, eastern to central Eurasia and mid-western part of North America and while during cool SAT years more inflow is concentrated over western and eastern part of the North Pacific, north-eastern Atlantic, central Eurasia and eastern part of North America. The difference in warm and cool SAT years shows more moisture convergence occurs through the Eurasian coast of North Pacific, North Atlantic side, eastern to central Eurasia into the Arctic causing a higher moisture convergence over central to eastern part of the Arctic Ocean. The composite analysis here also reveals the transport pattern of moisture into Arctic. For warm years moisture transport occurs over the North Atlantic through the Barents Sea and over North Pacific through Alaska coast while for cool years the transport occurs over western Eurasia along with the Alaska coast into the arctic. The difference between warm and cool composite shows that the changes in moisture transport is consistent with warming. The anticyclonic circulation over the Western Pacific and cyclonic circulation over Eastern Pacific help the convergence of moisture into Arctic through Bering Sea, Eurasia coast and mid-western part of North America. Strong cyclonic circulation near east coast of Canada and an anticyclone over northern

Atlantic along the western coast of Europe pushes the moisture through Greenland side and Barents Sea into the Arctic. Anticyclonic circulation near Siberian High advects warm and humid air through Eurasia into the Arctic (Figure 3.5).

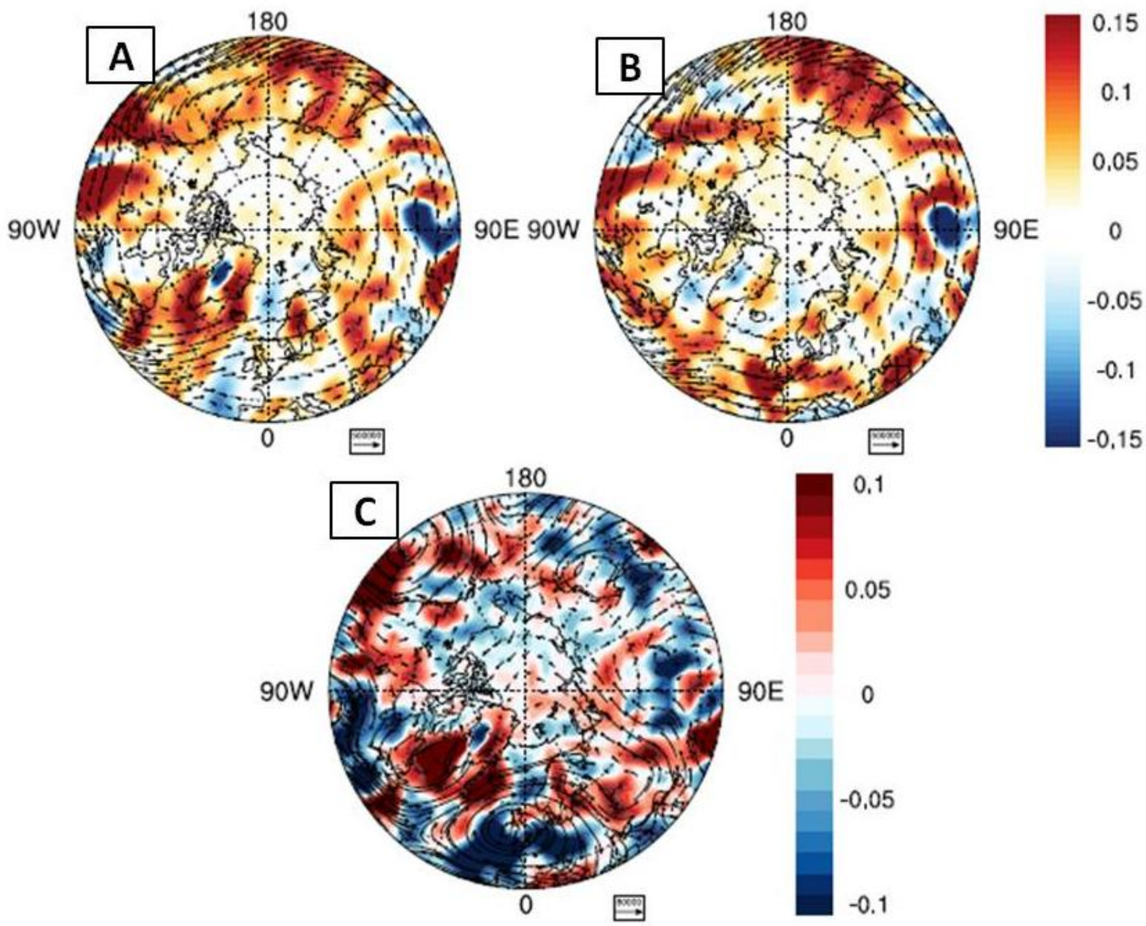

Figure 3.5: Composite of moisture transport represented by vectors over moisture convergence (in kg/hr-m^2) represented by shaded contour shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

The positive temperature anomaly over the Alaska, Eurasia and North Atlantic side of the Arctic (Figure 3.4, panel c) is consistent with increased moisture transport zones from mid-latitudes into the Arctic (Figure 3.5, panel c).

Composite analysis shows, for warm SAT years of latent heat convergence occurs over Northern Pacific, eastern Eurasia and North Atlantic side of the Arctic while for cool SAT years the convergence is concentrated over north-western Pacific, the Alaska coast, north-eastern Atlantic, and central Eurasia. Differences between warm and cool composites reveal higher inflow of latent heat energy over North Pacific through Eurasia, North Atlantic and eastern to central Eurasia region into the central to eastern Arctic Ocean. It also demonstrates the transport pattern of vertically integrated latent heat from mid-latitudes into Arctic. For warm years latent heat transport occurs over North Atlantic through the Barents Sea and over the North Pacific through Alaska while during cool years the transport occurs over western Eurasia along with the Alaska coast into the Arctic. The difference in warm and cool composites reveals the change in latent heat transport patterns to cause warmer years. The anticyclonic circulation over the Western Pacific and cyclonic circulation over the Eastern Pacific enhance the convergence of latent heat into Arctic through the Bering Sea, Eurasia and mid-western part of North America. Strong cyclonic circulation near the east coast of Canada and an anticyclone over Northern Atlantic along the western coast of Europe transport latent heat into the Arctic. The anticyclonic circulation near Siberian high advects warm and humid air through Eurasia into the Arctic (Figure 3.6).

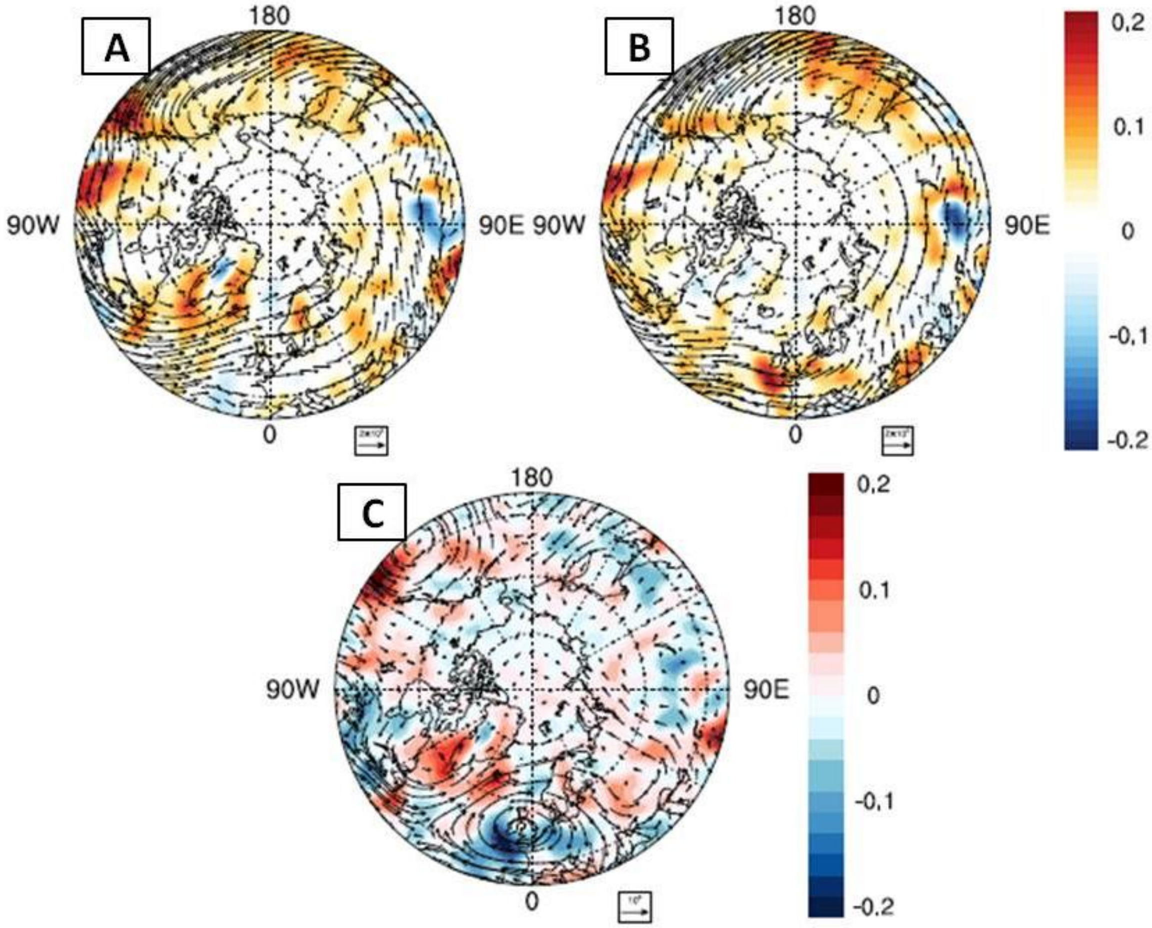

Figure 3.6: Composite of latent heat transport represented by vectors over latent heat convergence (in 10^3 W/m^2) represented by shaded contour shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

The spatial distribution of potential energy convergence and transport pattern from mid-latitudes into the Arctic are displayed in the following figure (Figure 3.7).

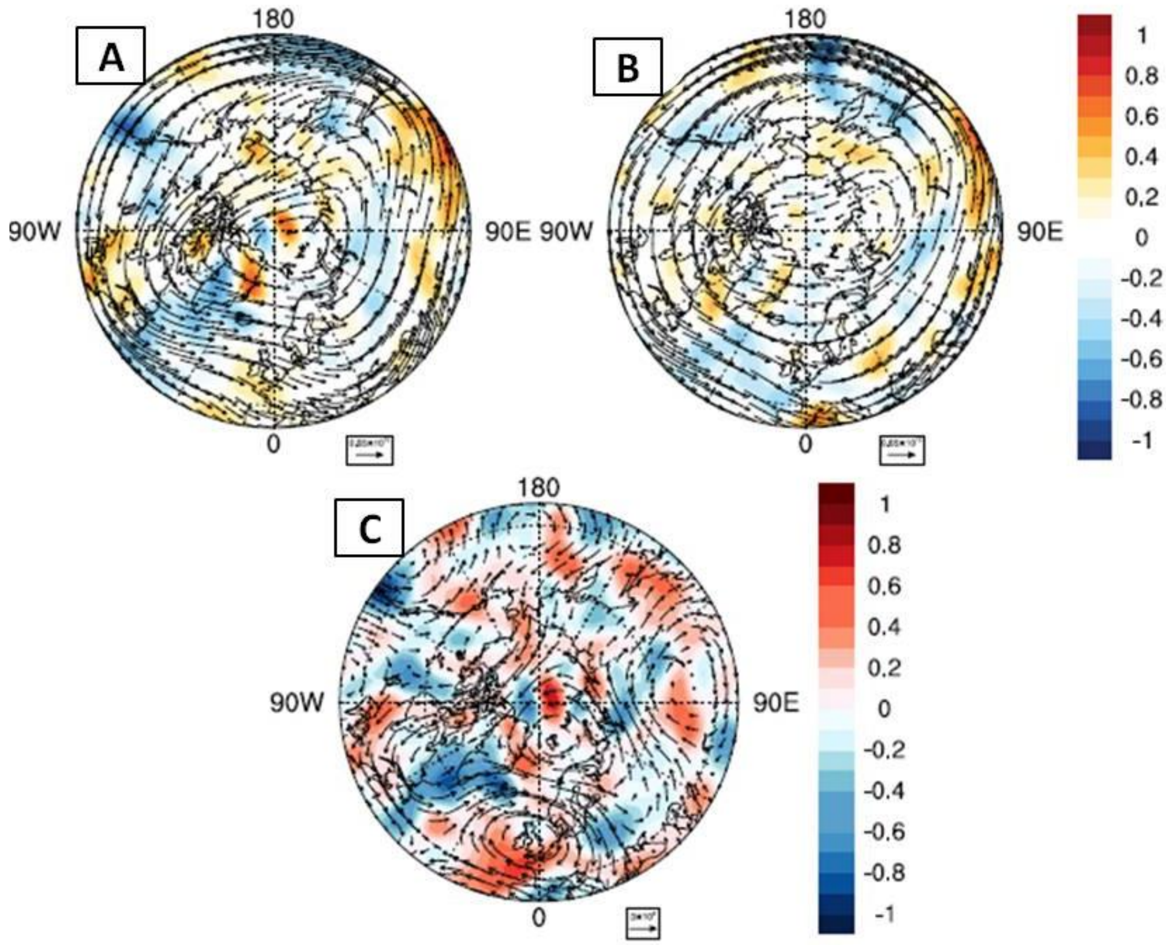

Figure 3.7 Composite of potential energy transport represented by vectors over potential energy convergence (in 10^3 W/m^2) represented by shaded contour shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

Figure 3.7 shows that for warm SAT years, the potential energy enters the Arctic through the Bering Sea, western Eurasia, eastern North America and the North Atlantic through Barents Sea into Arctic with higher convergence values at central to eastern part. During the cool years the convergence of potential energy over the North Pacific, western Eurasia, eastern Greenland coast and eastern Eurasia is lower than the warm years resulting in lower convergence of potential energy over central and western Arctic Ocean. The difference between warm and cool phases shows higher potential convergence for the warm cases occurs over North Pacific through the Bering Sea, central Eurasia and Barents Sea into the central Arctic Ocean. During warm SAT cases, a strong transport of potential energy occurs through Eurasia and the North Pacific over the central and Bering Sea side of Arctic while for cool phase the transport is confined across the Eurasia into the central Arctic. The enhanced warm temperature anomaly zone (figure 3.4, panel C) over eastern Eurasia, Alaska and Bering Sea side of the Arctic accompanies strong advection of potential energy through the Northern Pacific for prominent anticyclonic circulation over western Pacific and cyclonic circulation over the eastern Pacific. Another strong anticyclone near Siberian high helps in advection of potential energy into the central Arctic Ocean through the central Eurasia (Figure 3.7, panel C).

The spatial distribution of enthalpy convergence and transport pattern from mid-latitudes into the Arctic is shown in the next figure (Figure 3.8).

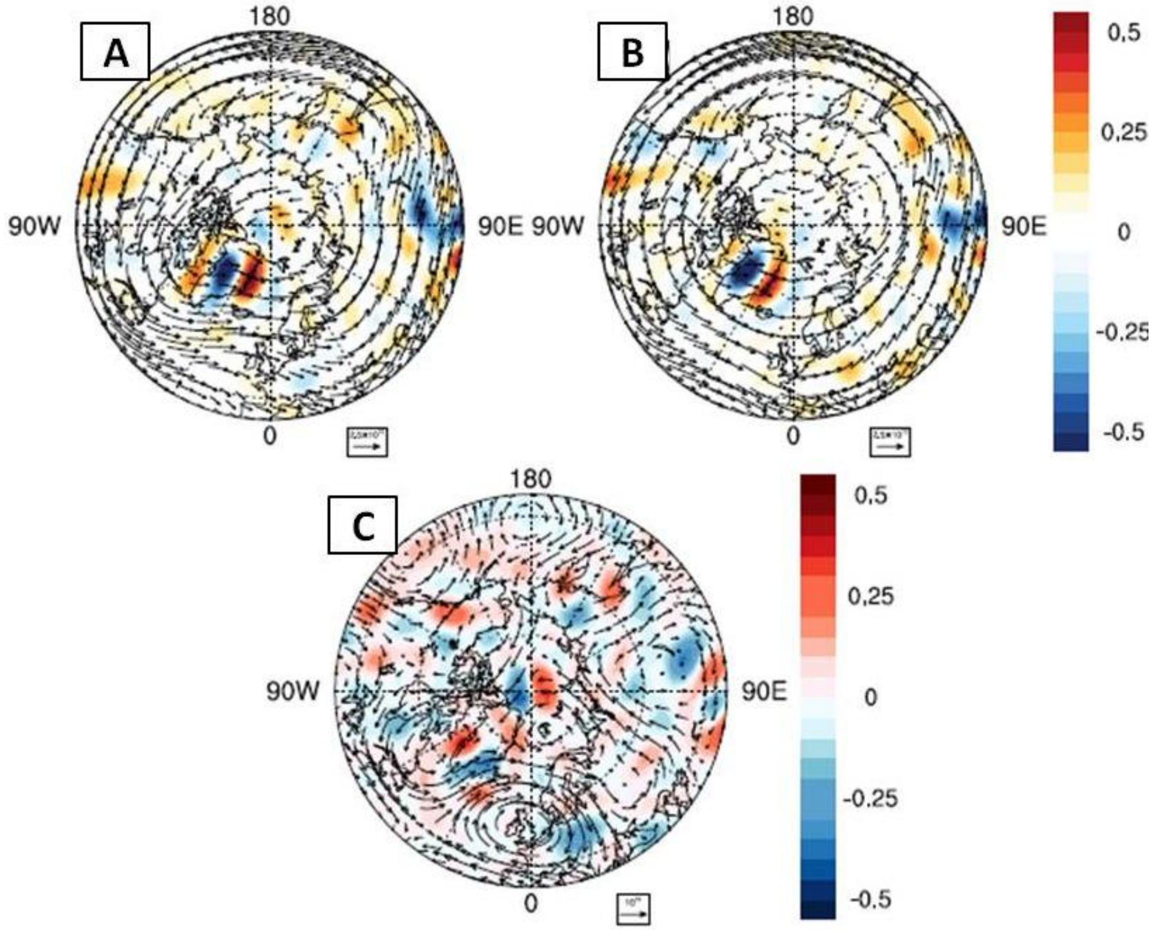

Figure 3.8: Composite of enthalpy transport represented by vectors over enthalpy convergence (in 10^4 W/m^2) represented by shaded contour shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

The composite analysis of enthalpy convergence shows higher Enthalpy convergence occurs over North Pacific through Bering Sea and Eurasia into central Arctic for warm SAT years while for cool SAT years all these regions show lower enthalpy convergence into the Arctic. Difference between positive and negative phase reveals increase in enthalpy convergence over the Bering Sea side via enhanced convergence through North Pacific as well as over Barents Sea and Eurasia side of the Arctic Ocean. The composite also shows during warm SAT phase, strong transport of enthalpy occurs through Eurasia and North Pacific across the central and Bering Sea side of Arctic and for cool phase the transport is confined to Eurasia across the central Arctic. Composite for the difference between warm and cool phases demonstrates (Figure 3.8, panel c) regions over eastern Eurasia, Alaska and Bering Sea side of the Arctic encompasses strong advection of enthalpy through northern Pacific for prominent anticyclonic circulation over western Pacific and cyclonic circulation over the eastern Pacific. Another strong anticyclone near Siberian high helps in the advection of enthalpy into the central Arctic Ocean.

So, different dynamic factors play distinct role over different region over Arctic to cause warm SAT years during spring transition period. During warm SAT years the moisture and latent heat convergence increase mostly over central Arctic as well as over the Atlantic and Eurasia side of the Arctic resulting in possible positive radiative forcing due to enhance moisture and latent heat. Whereas sensible heat flux due to convergence of enthalpy and potential energy advects near Bering Sea and Eurasia side of the Arctic to impact the SATs.

In this spatial distribution of convergence, noises arise in the calculations due to presence noises in the employed parameters over the Arctic.

3.3.2. Effect of Large Scale Circulation on Local Thermodynamic Processes:

Composite analysis of different thermodynamic parameter is performed to examine the influence of large scale atmospheric dynamics on local thermodynamic mechanisms over Arctic to regulate the surface energy budget. Corresponding spatial distribution of cloud cover, radiative and non-radiative heat fluxes over the Arctic from composite analysis reveals the impact of thermodynamic parameters on interannual variation of SAT.

According to composite analysis of cloud cover during warm SAT phase cloud cover is higher over North Pacific, Eurasia and North Atlantic side of the Arctic and for cool SAT phase more cloudiness is seen over Alaska and Pacific side of the Arctic. The difference in warm and cool phase shows higher cloud cover over North Atlantic and Barents Sea side as well as over parts of central and western Eurasia, central North America and Eastern Eurasia is seen that can contribute in warming over these regions. The higher cloudiness over the North Atlantic side of the Arctic (Figure 3.9) is similar to higher moisture and latent heat convergence zones supporting the fact of the contribution of enhanced warm and moist air advection over this region causes increased total cloud cover.

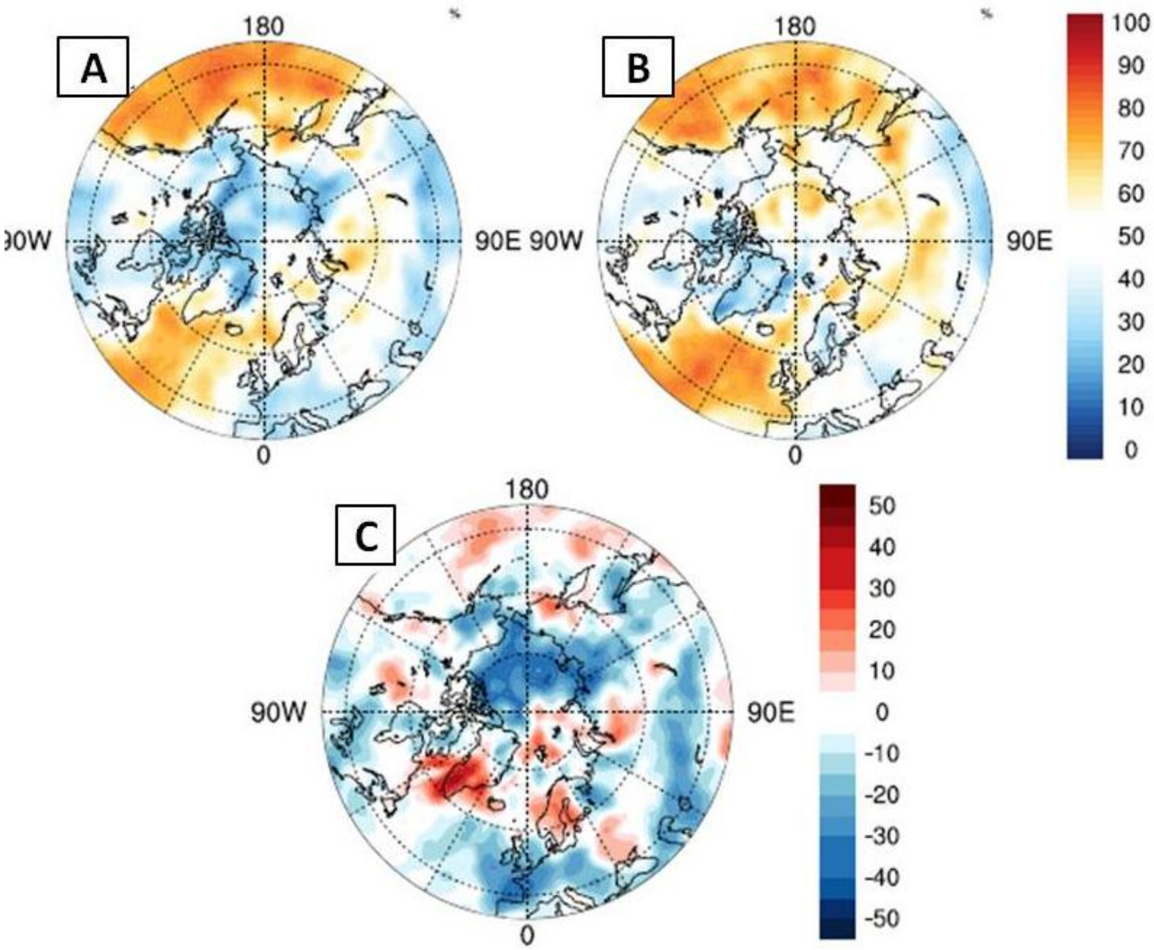

Figure 3.9: Composite analysis for cloud cover shows their spatial patterns corresponding to SAT variability during (a) warmer SAT phase (b) cooler SAT phase and (c) difference between warm and cool SAT phases.

The cloudiness can in turn impact the surface radiation budget. Consistent spatial distribution from composite of downwelling longwave radiation with the higher cloud covered region indicate that due to enhanced greenhouse effect by increased cloudiness over the North Atlantic and Barents Sea side of Arctic, central North America and central to western Eurasia is to is trapping the outgoing longwave radiation to increase the downwelling longwave radiation flux and SAT (Figure 3.10).

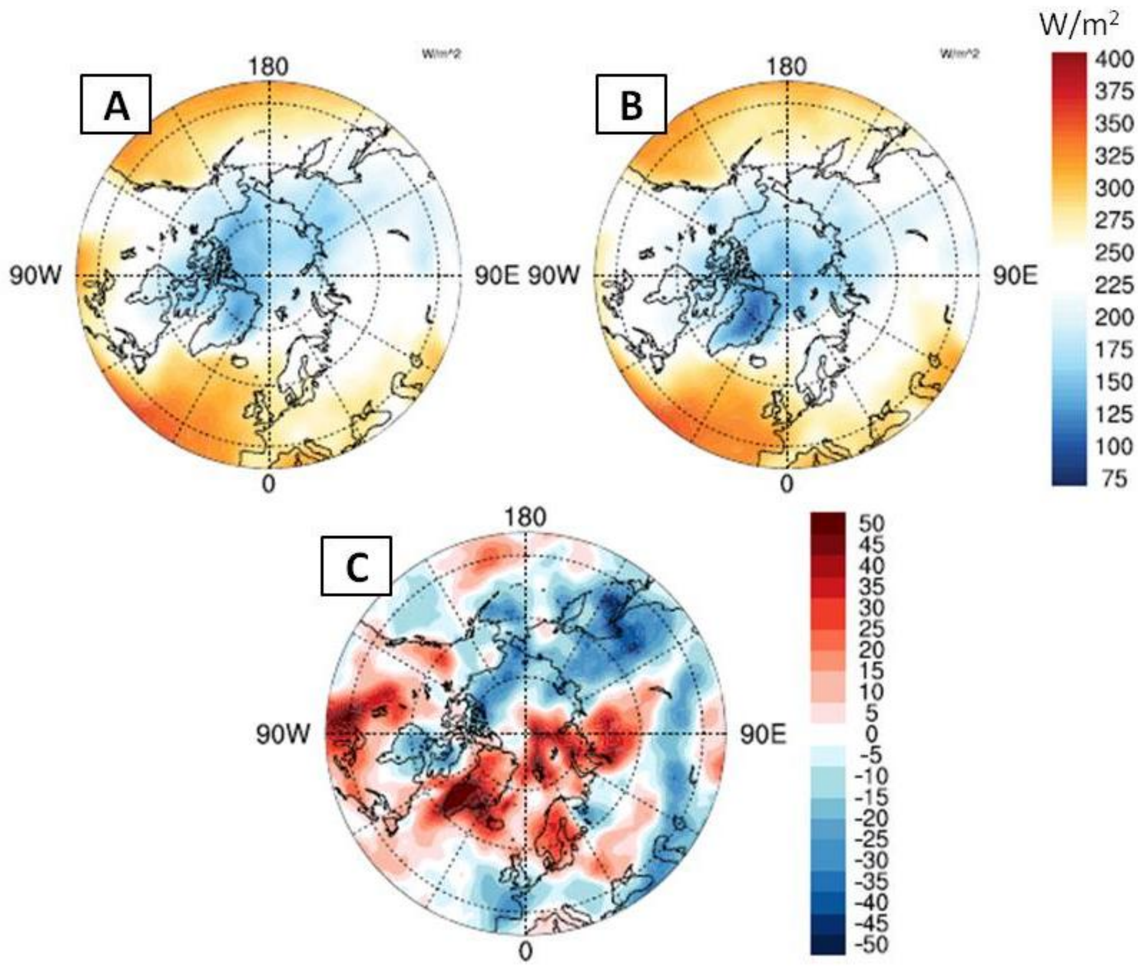

Figure 3.10: Composite analysis for downwelling longwave radiation flux (in W/m$^{2)}$ shows their spatial patterns corresponding to SAT variability during (a) warmer SAT phase (b) cooler SAT phase and (c) difference between warm and cool SAT phases.

Cloudiness also impacts the incoming shortwave radiation as some part of the incoming radiation is reflected back from the clouds. The composite of downwelling shortwave radiation reveals, over the region of lower cloud cover more incoming solar radiation can reach to the ground and higher values in downwelling shortwave radiation flux contribute in the warming (Figure 3.11).

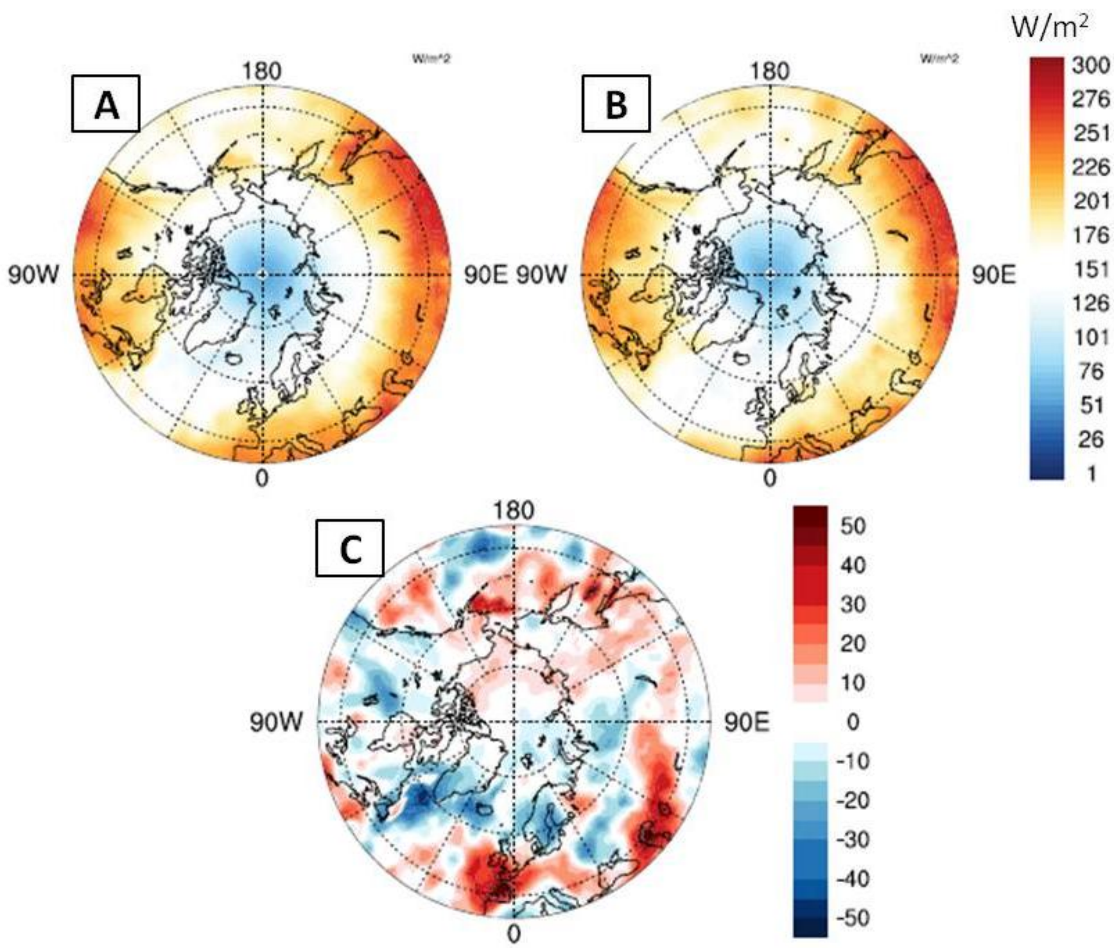

Figure 3.11 : Composite analysis for downwelling shortwave radiation flux (in W/m$^{2)}$ shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

Figure 3.11(panel C) shows, the Bering Sea, Alaska, eastern Eurasia and North Pacific side of the Arctic receives more downwelling shortwave radiation to create warmer SATs over these particular regions. Downwelling shortwave radiation does not contribute in warming over the North Atlantic side of the Arctic as less incoming solar radiation reaches to the surface due to higher cloudiness.

Another important parameter is the surface albedo to regulate the net shortwave radiation flux at the surface. The spatial distribution of sea ice concentration over the Arctic reveals the reduced sea ice area. For higher sea ice cover the surface would have higher albedo and can reflect back a considerable amount of incoming solar radiation. But the reduced sea ice would introduce lower surface albedo and less reflection of incoming solar radiation flux can result increased absorption of incoming solar radiation flux at the surface.

The sea ice concentration composite of the difference between warm and cool phases demonstrates (Figure 3.12) higher concentration of sea ice towards the Alaska side of Arctic and lower sea ice concentration towards the North Atlantic and Eurasia side of the Arctic indicating reduced sea ice over the Eurasia and North Atlantic side while more sea ice cover over the Alaska and North Pacific side of the Arctic.

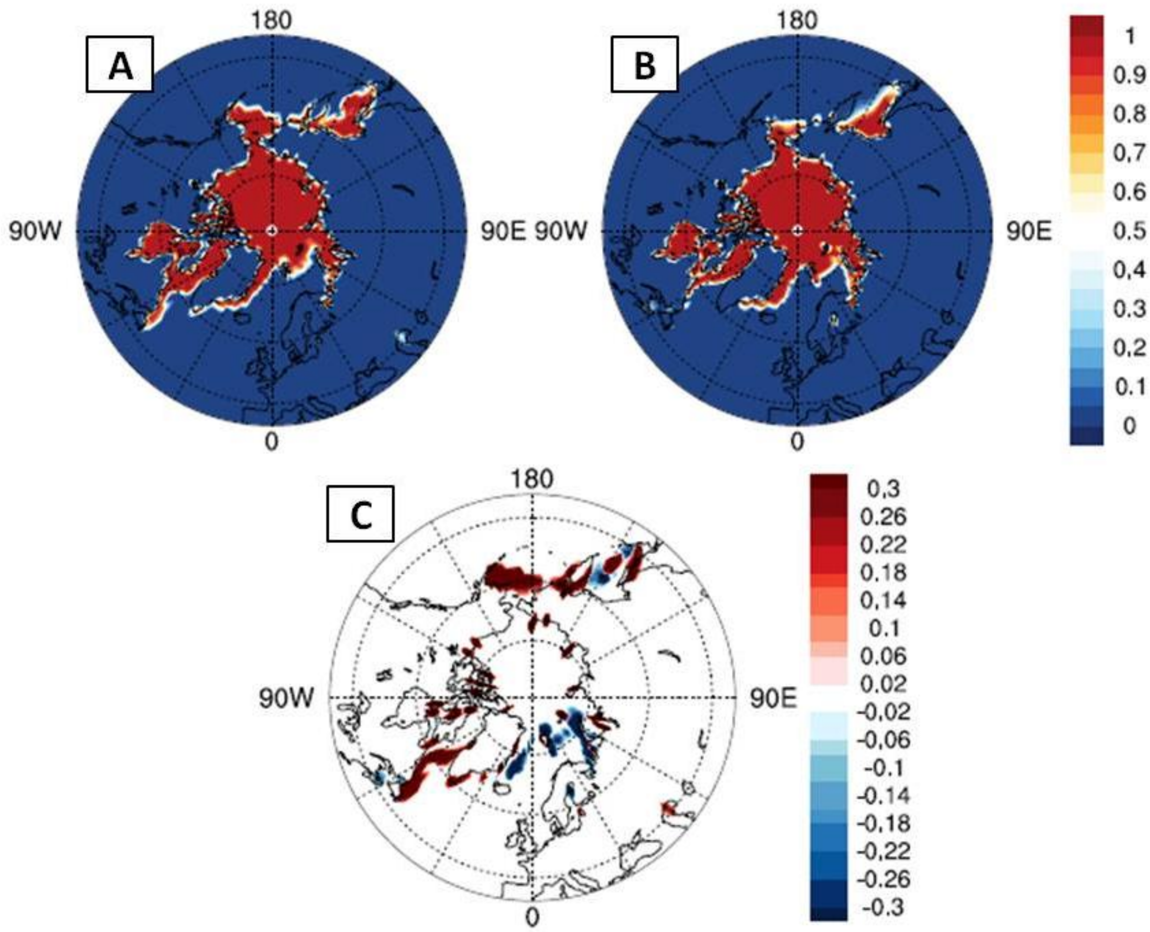

Figure 3.12: Composite analysis for sea ice concentration shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

Comparison between sea ice distribution with cloud covers (Figure 3.9, panel C), shows reduced sea-ice over the cloudier the North Atlantic side, while the clear sky region is experiencing higher sea ice cover over the North Pacific side. This support the positive cloud radiative forcing can impact earlier melting of sea ice during spring (Zhang et al.

1997). The effect of surface albedo for sea ice is patterns are consistent with the upwelling shortwave radiation composites. The composite corresponding to difference between warm and cool SAT shows, more upwelling shortwave radiation over the more sea-ice covered Alaska and North Pacific side and less upwelling shortwave radiation over the reduced sea-ice regions over Eurasia and North Atlantic side (Figure 3.13).

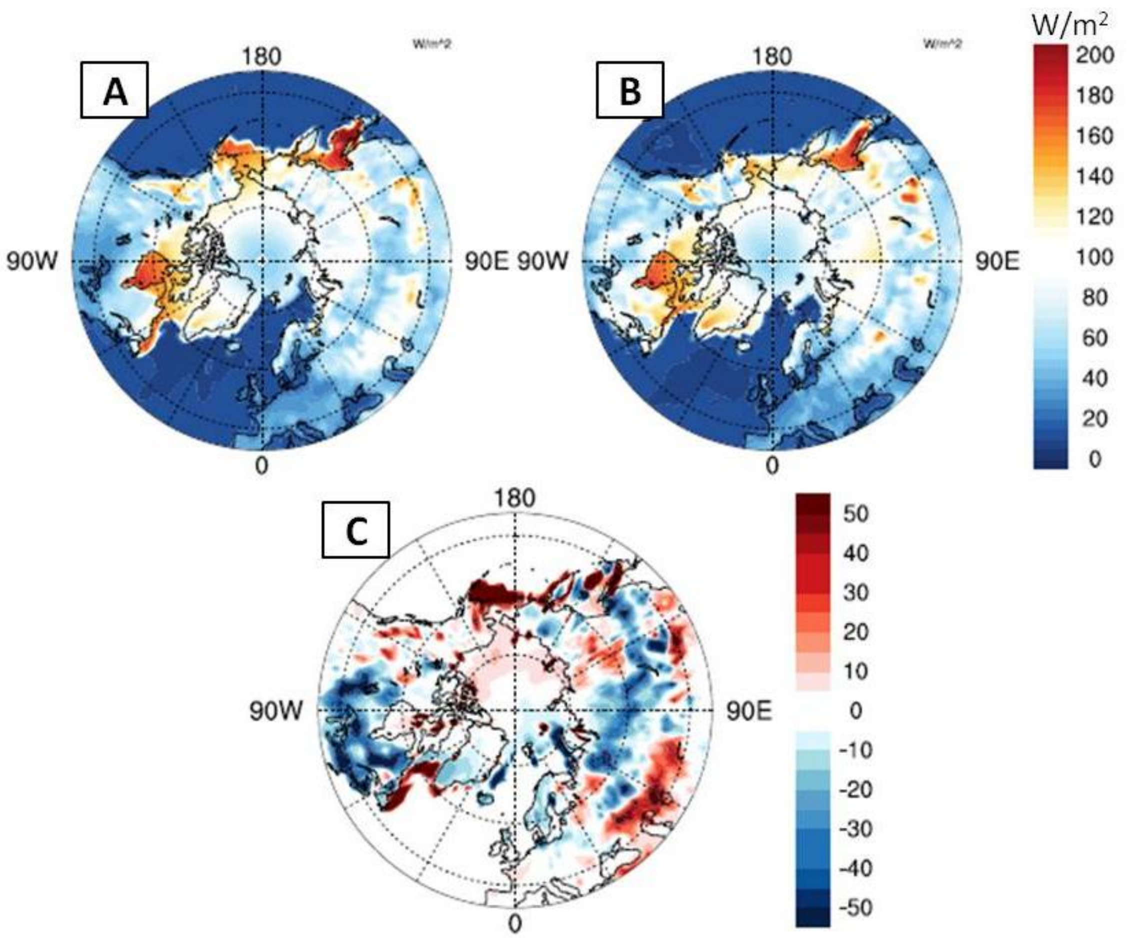

Figure 3.13: Composite analysis for upwelling shortwave radiation flux (in W/m$^{2)}$ shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

The complex interaction of different feedback processes due to cloudiness and surface albedo regulate the net radiation flux at surface. The composite of net downwelling radiation flux shows higher values over the North Atlantic side, Eurasia and North America contributing in warming over these regions while the value is lower for Alaska and North Pacific side of the Arctic (Figure 3.14, panel C)

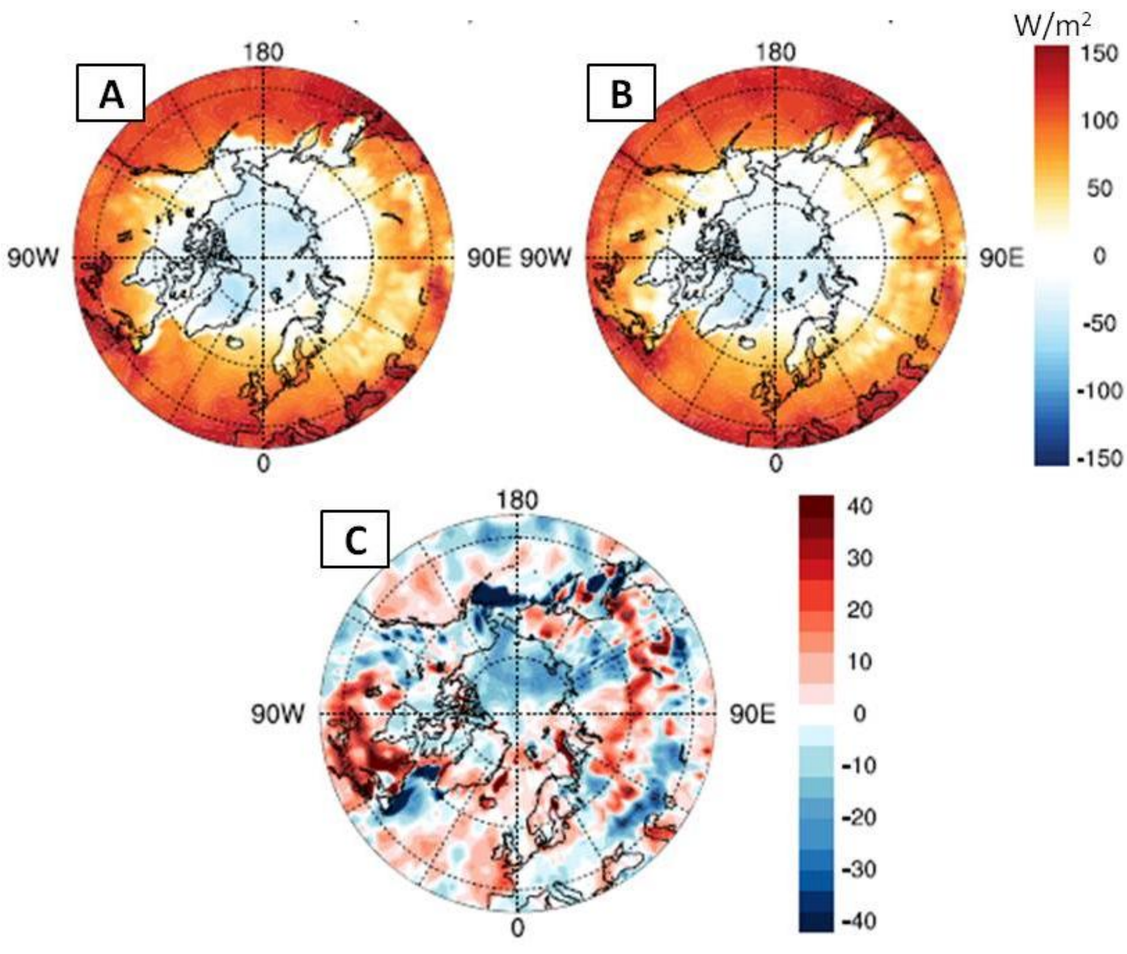

Figure 3.14: Composite analysis for net incoming all-wave radiation flux (in W/m$^{2)}$ shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

According to the figure 3.14,panel C; the spatial pattern indicates the net downwelling radiation flux dominates for the surface warming only towards the North Atlantic, parts of North America and Eurasia side of the Arctic, not over the whole Arctic. This indicates the increase in moisture and latent heat convergence leading to enhanced cloudiness are important factor to cause warm SAT phase over the North Atlantic side. Increased downwelling longwave radiation flux over this region as well as reduced upwelling shortwave radiation for decrease in surface albedo take important role in causing warmer SATs over this region of the Arctic.

Exchange in turbulent heat fluxes between the surface and the overlying atmosphere is also important contributing factor to regulate the surface energy budget. Advection of warm air into the Arctic from mid-latitudes is causing warmer atmospheric temperature over the Arctic with a downward temperature gradient. This causes enhanced sensible heat flux from warmer atmosphere to the surface over the Arctic. Composites of downward sensible heat flux over the Arctic shows enhanced downward sensible heat flux from warmer atmosphere to surface to contribute in considerable warming over the whole Arctic (Figure 3.15, panel C).

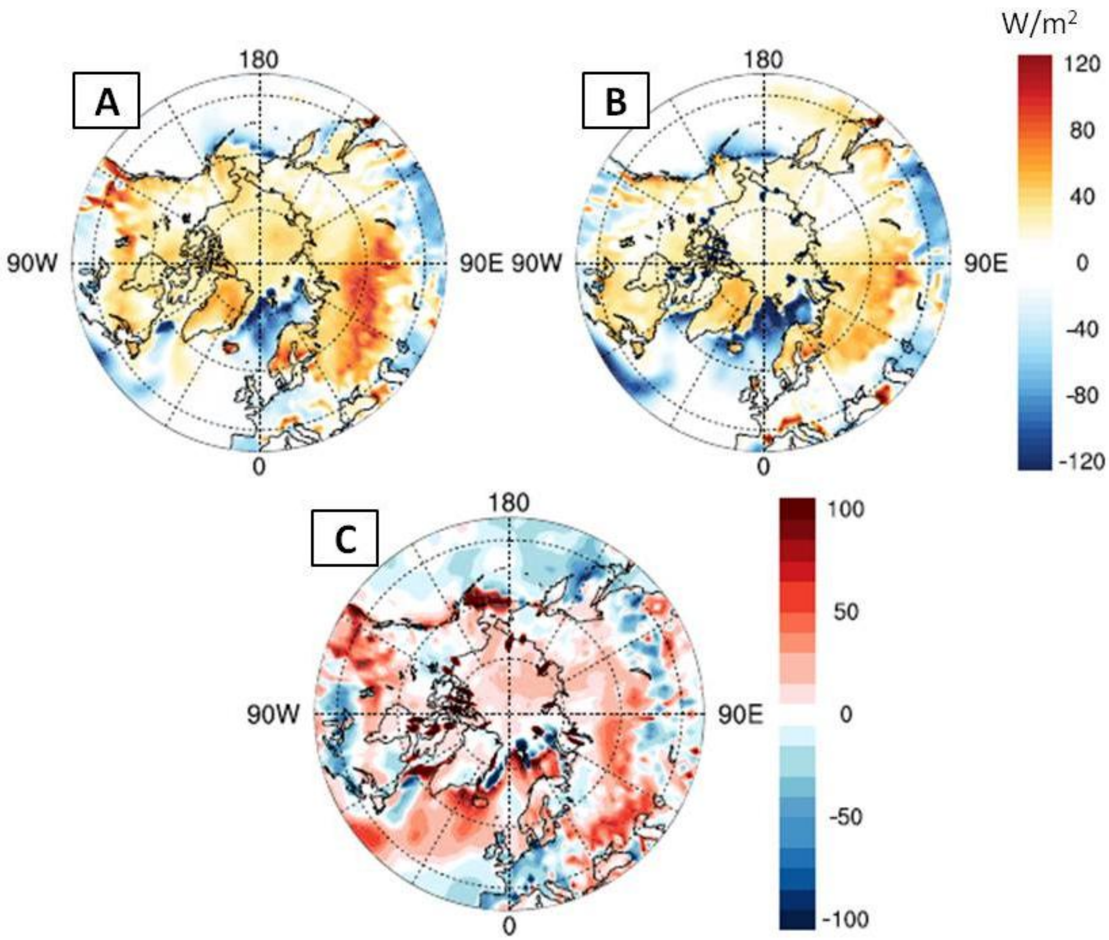

Figure 3.15: Composite analysis for downward sensible heat flux (in W/m$^{2)}$ shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

Spatial distribution from composites of downward latent heat flux indicates it does not have prominent effect to contribute in warm Sat phases over the Arctic. It has cooling effect towards the edge of the Arctic Ocean over Eurasia and North Atlantic side (Figure 3.16, panel C).

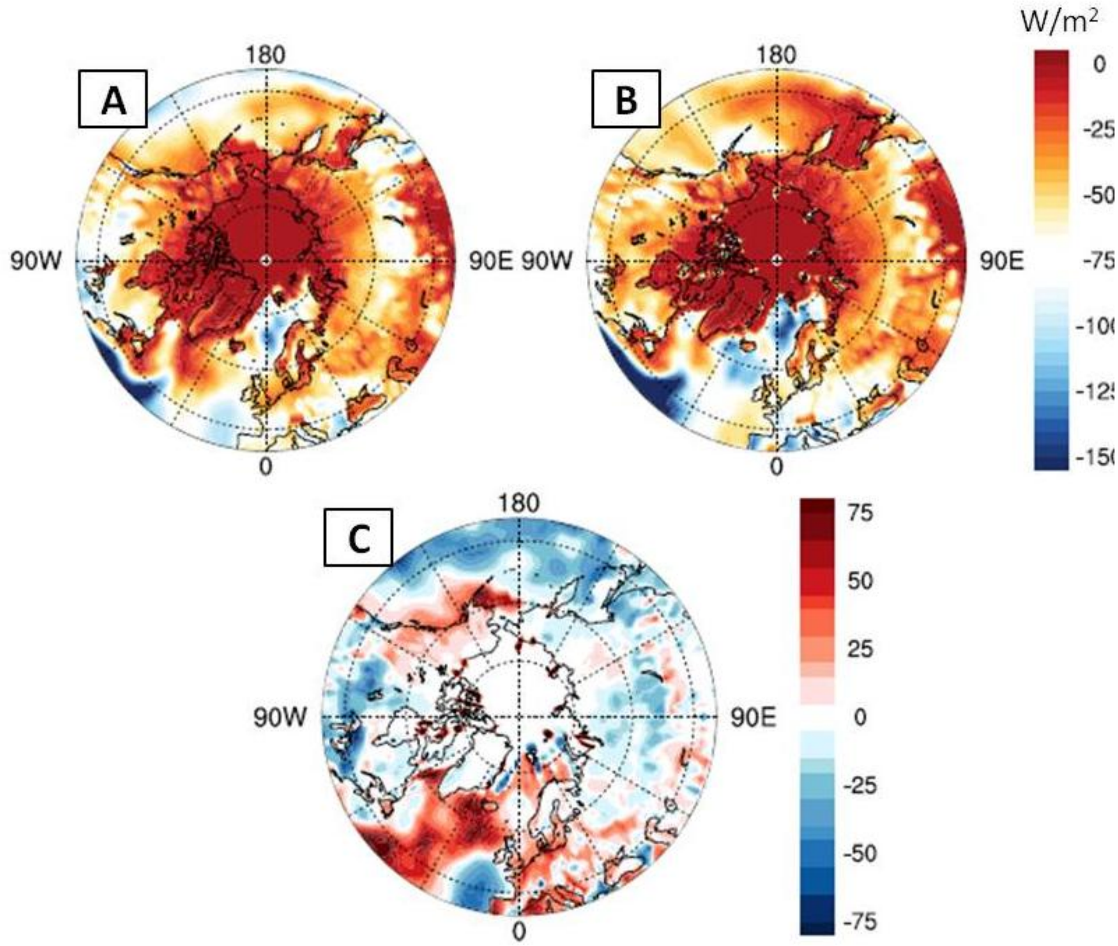

Figure 3.16: Composite analysis for downward latent heat flux (in W/m^2) shows their spatial patterns corresponding to SAT variability during (a) warm SAT phase (b) cool SAT phase and (c) difference between warm and cool SAT phases.

The edge of the Arctic towards the Eurasia and North Atlantic side also experience the retreat in sea ice resulting exposed open water area. This would cause increase in evaporation and thus upward transfer of latent heat flux from surface to the atmosphere. Over this area latent heat flux contribute in cooling of the surface during warm SAT phase (Figure 3.16, panel C).

3.4 Summary for Important Physical Factors to Cause Inter-annual Variability:

Composite of contributing dynamic and thermodynamic factors to regulate the surface energy budget demonstrates their regional importance to cause warm SAT years. This composite analysis helps in understanding the interannual variability warming over the Arctic and reveals the spatial distribution of contributing physical parameters to regulate this pattern.

For warm SAT years, increase in moisture and latent heat flux over the North Atlantic and Eurasia side is associated with increase in cloud cover and enhancement in downwelling longwave radiation due to enhanced greenhouse effect by clouds. This contributes to cause warmer SATs over this region. But enhanced cloud cover decreases incoming shortwave radiation over the North Atlantic side causing cooling of the surface. Reduced sea ice on North Atlantic side leads to lower surface albedo resulting in higher absorbance of incoming shortwave radiation. Cloudiness and enhanced greenhouse effect over the region has impact on reduction of sea ice. The downward sensible heat flux from warmer atmosphere to the surface is another factor to contribute in warming events over the North Atlantic side of the Arctic.

Over the Pacific side of Arctic less moisture and latent heat convergence is associated with dominance of clear sky and more incoming shortwave radiation can reach to the surface to contribute in warming. In contrast to the North Atlantic side, less melting of sea ice on the Pacific side leads to high surface albedo and more upwelling shortwave radiation escape from the surface. Negative surface albedo forcing causes surface cooling over this region. Transport of dry static energy from mid-latitudes is important for warming over North Pacific and Alaska side of the Arctic. Warm air advection creates warmer atmosphere over the whole Arctic thus has similar contribution in surface warming over the North Pacific side like the Atlantic side. It results in surface warming by enhanced sensible heat flux from warmer atmosphere to the surface.

The net radiative flux due to enhanced downwelling longwave radiation flux and increased absorption of shortwave radiation is mostly important for warming over the North Atlantic and Eurasia side. Effect of moisture and latent heat convergence regulate the cloud cover to impact the surface radiation budget over this region. But the impacts of these physical factors are different over the Pacific side. Here most important warming factors are incoming shortwave radiation due to less cloudiness and advection of dry static energy from the mid-latitudes.

This composite analysis demonstrates regional importance of the contributing dynamical and thermodynamical parameters to regulate the SAT variability during springtime and to cause extreme SAT events.

Chapter 4 : Discussion and Conclusion

The purpose of the study was to understand how the seasonal transition during springtime is changing over the Arctic in recent years and the importance of different physical processes in shaping the climatology and variation of the spring transition. Our investigation of different climate variables during spring revealed significant link between prevailing dynamic and thermodynamic conditions over the Arctic that influence the springtime transition by influencing the surface air temperature (SAT) field. The analysis shows linkage between the large scale circulation with regional physical and thermodynamic conditions to regulate the overall SAT field. Our analysis reveals the importance of contributing physical factors for springtime transition, considering previous studies and theories presented in the introduction chapter about the influence of large scale circulation on poleward moisture and energy transport along with complex interactions that cloud, albedo and radiation have on the Arctic surface energy budget to control the SAT.

4.1 Research Summary and Discussion

This study employs NCEP Reanalysis Dataset-2 to examine different atmospheric parameters for the study of the springtime transition. It focuses on variations in surface air temperature over the Arctic during spring to understand changes and variability in the seasonal transition in the context of surface warming and examines possible factors behind the change.

4.1.1. Changing Pattern in Arctic Spring Transition

The Arctic surface temperature displays an increasing trend over the study period (1979-2012). With shift in occurrence time of higher temperature, the springtime transition is getting earlier. This can impact the seasonal climatology by favoring an early onset to summer, which lengthens the period of sea-ice and snow cover melting and vegetation growing over the Arctic.

Analysis of springtime SAT reveals an interannual variability superimposed over the warming trend. Rapid and consistent increasing trend in SAT concludes that the spring transition is changing over time and the change is most prominent during mid-March to mid-April period over the Arctic.

4.1.2. Contributing Physical Parameters in Shaping the Climatology

To investigate the dynamical causes behind the change in seasonality during springtime, the atmospheric large scale circulation was documented to understand the energy and moisture transport into the Arctic from the mid-latitudes.

It has been observed from the analysis of transport processes that moisture and latent heat convergence have a significant impact on a changing seasonal climatology. Moisture and latent heat convergence into the Arctic is increasing over time which in turn can impact the regional thermodynamics by increasing cloud cover over the Arctic. Though the trend in dry static energy convergence is mostly increasing, it is not consistent throughout the period of study. Phases of the Arctic Oscillation and meridional temperature gradient regulate the sensible heat transport into the Arctic. So, from a dynamical point of view, the influence of moisture, latent heat and dry static energy convergence into Arctic can impact the Arctic surface energy budget and springtime SAT field.

Analysis of thermodynamic processes that impact the seasonal climatology of Arctic is also summarized in this section. With increasing convergence of moisture and latent heat flux over the Arctic, the total cloud cover increases during the period of mid-March to mid-April. This in turn warms the SAT field by increasing downwelling longwave radiation. Shortwave radiation is reduced by increased cloud cover as more incoming solar radiation is reflected back to the space. There is increased absorption of solar radiation at the surface from reduced sea ice and snow cover. The net radiation budget shows a positive anomaly in last decade of the study, which provides increased energy for the surface energy budget. Another factor impacting the surface energy budget is the increase in downward sensible heat flux that results from a warmer atmosphere due to poleward transport of warm air from lower latitudes.

As discussed in the previous chapters, atmospheric dynamics can impact the thermodynamic mechanisms over a region. Consistent with the impact of dynamics, the surface radiation budget of Arctic is influenced by increased humidity, cloudiness and warm air advection.

In conclusion both dynamic and thermodynamic factors influence the surface energy budget to regulate the seasonal climatology during the spring transition period.

A strong linkage exists between the contributing dynamic and thermodynamic factors to regulate the seasonal climatology under warming climate conditions. The flowchart between different contributing physical factors demonstrates the importance and linkage between contributing factors to regulate the warming trend (Figure 4.1).

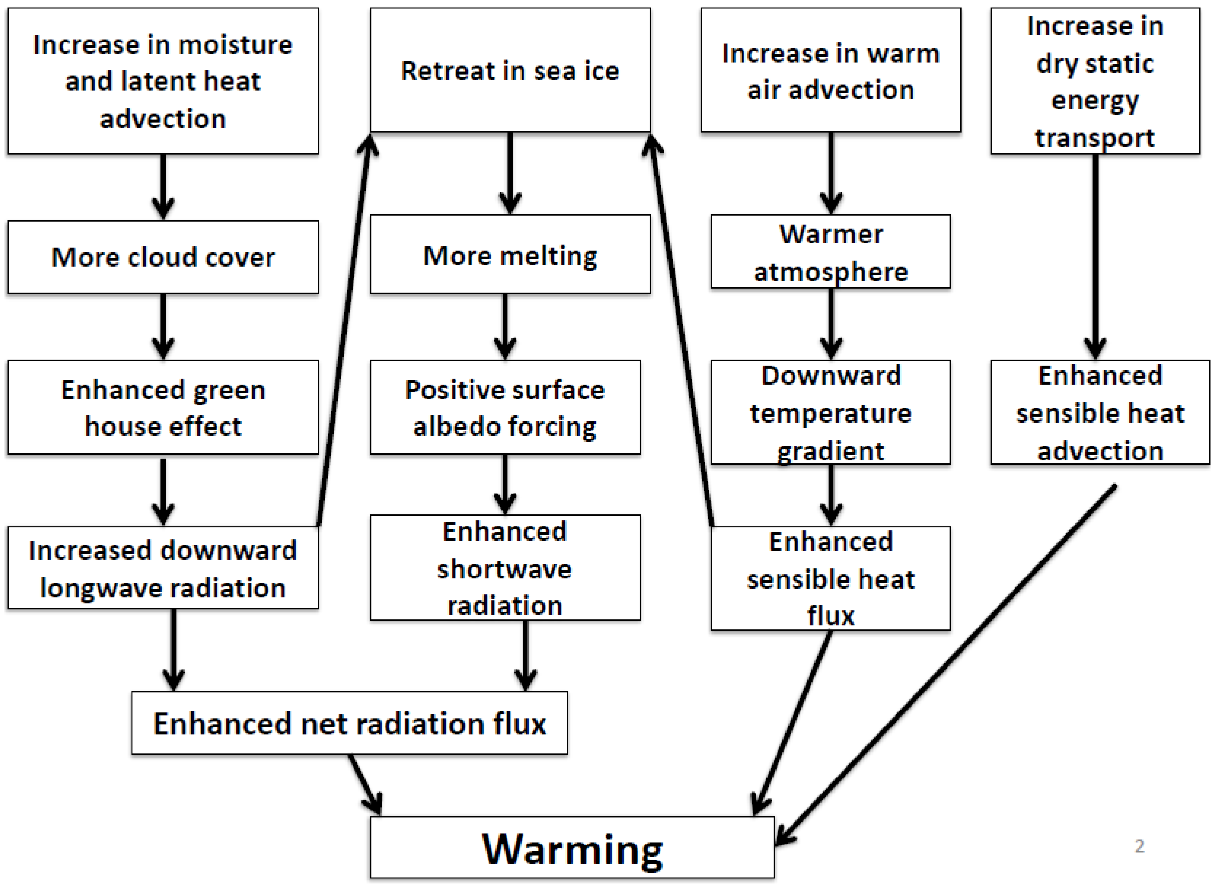

Figure 4.1: Important physical parameters in shaping the springtime climatology show the linkage between dynamic and thermodynamic factors to regulate the surface warming.

4.1.3. Causes behind Year-to-Year Variability in Temperature

The conclusion presented in the previous section reveals that both dynamic and thermodynamic factors are important in shaping the springtime climatology and contributing in the surface warming. The composite analyses of those contributing physical factors were performed to examine the causes behind the interannual variability superimposed over the springtime warming trend. In this section we present the regional importance of the contributing physical parameters in regulating the warm and cool SATs to cause year-to-year variability.

The spatial pattern of SAT shows a warming trend over the whole Arctic. But the composites of different dynamic and thermodynamic factors show substantial differences between warm and cool phases of SAT during the study period. Differences in spatial distribution of climate parameters between warm and cool SAT years reveal the regional importance in the corresponding climate parameters to regulate the surface warming. We discuss here about the important physical factors to regulate the warming over the Atlantic side of the Arctic and the Pacific side of the Arctic.

The North Atlantic side of the Arctic is a higher convergence zone of moisture and latent heat. Over this region, the warmer SAT years is accompanied with enhanced cloudiness, increased downwelling longwave radiation, enhanced absorption in shortwave radiation due to reduced sea ice to cause more surface warming. The downward sensible heat flux has impact in the warming over the whole Arctic. An advection of warm air over the Arctic causes higher atmospheric temperature and downward sensible heat flux over this region. The flowchart between the important causes behind warming events over the North Atlantic side of the Arctic also depicts the linkage between the dynamic and thermodynamic factors to regulate the warming process over the North Atlantic side of the Arctic (Figure 4.2).

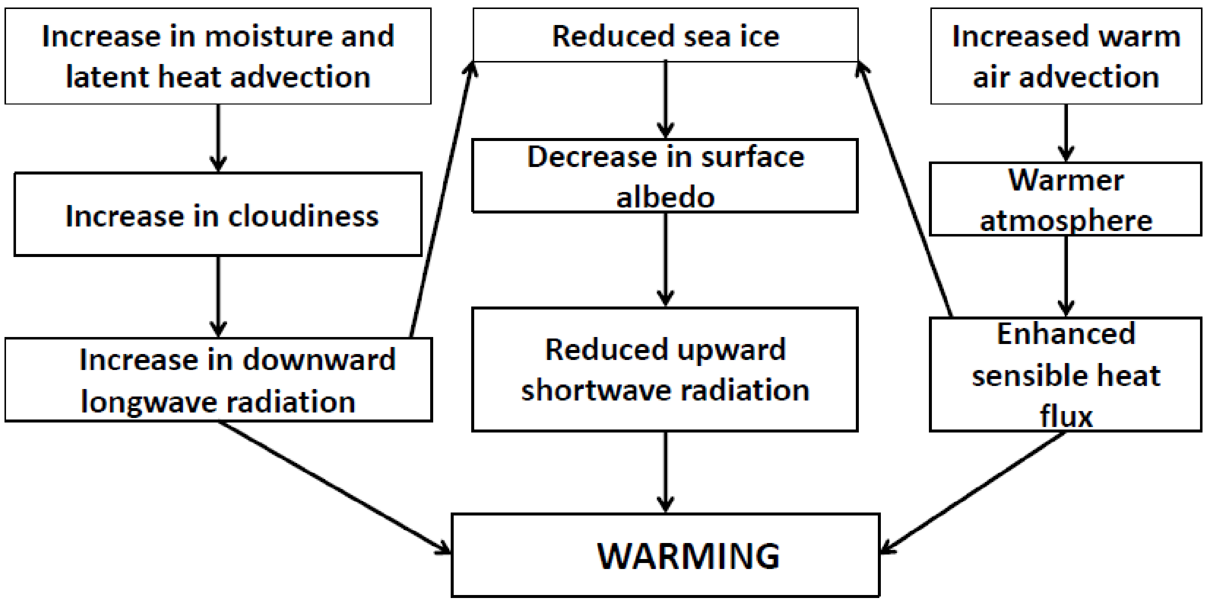

Figure 4.2: Important dynamic and thermodynamic factors to impact the warming over the North Atlantic side of the Arctic shows the regional importance of different physical parameters.

During the warmer SAT years, an opposite climate condition is seen over the Alaska and North Pacific side of the Arctic. The Alaska side and North Pacific side of the arctic experiences less moisture and latent heat convergence but higher convergence of sensible heat flux. The contribution of the specific physical condition differs on the Pacific side of the Arctic to cause warming events.

The dry static energy transport into the Arctic is most important to cause warm cases over the Pacific side of the Arctic. Also the less cloud covers due to reduced moisture and latent heat transport, results in enhanced downwelling shortwave radiation reaching to the surface. The sensible heat flux has similar influence over this region as the warm air advects into the whole Arctic resulting in a warmer atmosphere. This introduces enhanced downward sensible heat flux to impact the surface warming (Figure 4.3).

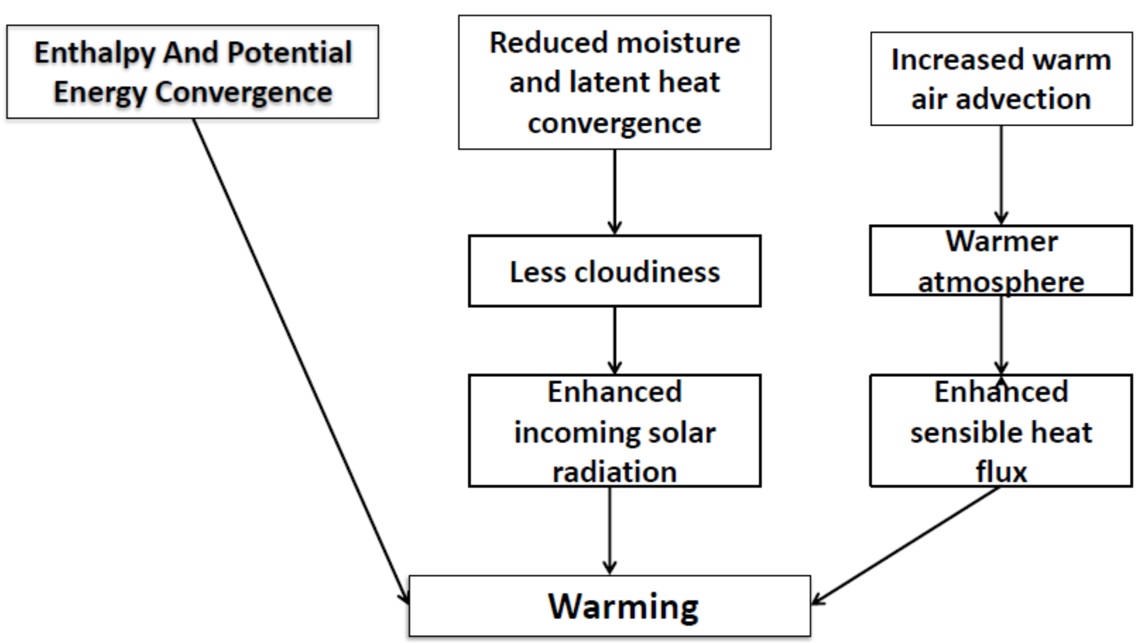

Figure 4.3 Important dynamic and thermodynamic factors to impact the warming over the Pacific side of the Arctic reveals regional importance of the different physical parameters.

The important physical factors to contribute in warming over the Pacific side of the Arctic (Figure 4.3) also show linkage between the contributing dynamic and thermodynamic parameters.

So, the contributing physical factors to cause year-to-year variability in the SAT trend are strongly regionally dependent. The interannual variability in SAT is also regulated by a strong linkage between dynamic and thermodynamic factors.

4.2 Future Work

Using reanalysis dataset reveals significant signal in analysis of seasonal climatology for springtime over the Arctic. Considering other reanalysis datasets for the same study can reinforce the finding. Also a modeling investigation would be beneficial for long term prediction of seasonal climatology for spring transition. A more detailed analysis using the similar approach can be done to understand influence of larger scale climate oscillation on the seasonal transition as well as decadal or multi decadal changes over the region for a better projection of seasonal transition in future.

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